EFFECTS OF ATMOSPHERIC CONTAMINATION ON THE PERFORMANCE OF CARBON BRUSHES ON COPPER SLIP RINGS

by

Philip Farr Grasser

United States
Naval Postgraduate School

THESIS

EFFECTS OF ATMOSPHERIC
CONTAMINATION ON THE PERFORMANCE
OF CARBON BRUSHES ON COPPER
SLIP RINGS

by

Philip Farr Grasser

October 1969

Effects of Atmospheric Contamination on the Performance of Carbon Brushes on Copper Slip Rings

by

Philip Farr Grasser
Lieutenant, United States Navy
B.S., United States Naval Academy, 1964

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
October 1969

ABSTRACT

The unsatisfactory performance of collector and commutator brushes in motor generators aboard nuclear submarines is introduced with the hypothesis that these difficulties are the result of atmospheric contamination. Following a survey of previously encountered contamination problems the experimental apparatus and procedures used to test this theory are described. Results of operation in eight simulated submarine environments are provided.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

ACKNOWLEDGEMENT

The kind assistance of Mr. George H. Gunnoe of General Electric Corporation, Mr. Lawrence E. Moberly of Westinghouse Electric Corporation, Assistant Professor Charles F. Rowell, Department of Material Science and Chemistry, Naval Postgraduate School, and Associate Professor Milton L. Wilcox, Department of Electrical Engineering, Naval Postgraduate School, is gratefully acknowledged.

I. INTRODUCTION

A recent industrial tour at the San Francisco Bay Naval Shipyard has brought to light an annoying, if not critical, fleet maintenance problem. Numerous reports of rapid brush deterioration and commutator and slip ring threading on Allis Chalmers 64-KW and 30/10-KW motor-generators and Safety Electric 64-KW motor-generators have been received by the Naval Ship Systems Command [1]. These units are aboard three classes of nuclear powered submarines. Overbrushing was suggested as a possible cause of these difficulties and removal of one brush from each commutator brushholder an interim solution [2]. This letter also makes reference to tests in progress on the Allis Chalmers sets at the Naval Ship Engineering Center, Philadelphia Division.

More recent correspondence [3,4] and telephone conversations with NAVSECPHILDIV personnel indicated that although some progress had been made, no exact cause of the problem had been uncovered. These investigations were quite extensive and had included changes in brush grades, brushholder design, spring pressure, current density, and slip-ring material.

Further inquiries indicated that although no statistical evidence had been compiled, the experience of NAVSEC personnel supported the proposition that collector problems occurred more frequently in nuclear submarines than aboard surface vessels, similarily equipped. A review of a voluminous computer readout obtained from the Navy Maintenance and Material Management System reinforced this idea [5].

Based on this evidence it was deemed prudent to investigate the theory that due to the extended submerged operations of nuclear powered

submarines, unusual atmospheric conditions aboard these vessels may well contribute to the collector problems presently being experienced.

II. SURVEY OF CONTACT THEORY

Due to the extremely complex nature of contact theory it was necessary to peruse the available literature in this area prior to investigating any particular facet. One of the prime objectives of any research should be the assistance of those individuals who will do future work on the subject being studied. To this end Refs. 6 and 7 must be cited.

Reference 6 is undoubtedly the finest electrical contact bibliography yet published. Under the guiding hand of Dr. Erle I. Shobert II of Stackpole Carbon Company, Committee B-4 of the American Society of Testing Materials has completed an exhaustive search of the science literature, including foreign publications, from 1835 to 1963. The comprehensive abstracts included in these volumes are an outstanding aid to an otherwise almost impossible task.

Reference 7 authored by Dr. Ragnar Holm also deserves special mention. Dr. Holm has dedicated over forty years of meritorious effort to the search for truth in the contact field. His leadership and numerous contributions have been a benchmark by which others judge their work. With this in mind it is not surprising that when conflicts arise in the explanation of almost any aspect of contact theory, Dr. Holm's thoughts must be carefully weighed.

A. CONTACT AREA

In discussing the interface between carbon brushes and a copper slip ring an initial consideration is the area of actual contact. The surfaces of both members will contain numerous microscopic asperities despite the most careful lapping. Careful observation of the stationary

contact surfaces under mechanical and electrical load would disclose three distinct areas. The apparent area, A_a, is the macroscopic brush face area. The load-bearing area, A_b, is the sum of the many deformed contact points produced by the spring or load force. This area now carries an average pressure $\bar{p}$. The pressure on individual points will vary depending upon whether plastic or elastic deformation has occurred. Letting H be the contact or Meyer's hardness of the brush, equation (1) and (2) can be derived [8].

$$P = k\ H\ A_b \text{ grams} \tag{1}$$

$$\bar{p} = k\ H \text{ grams/sq cm} \tag{2}$$

In equations (1) and (2) k accounts for the ratio of elastic to plastic deformation. Measured values of k between 0.1 and 0.3 are most frequent.

A large portion of A_b is covered with an insulating film during operation in air. The conducting area, A_c, is defined as the sum of those small regions within A_b which have either no film coverage (metallic contact), or a thin film ($\simeq$ 20 A) called quasi-metallic contact.

The relative sizes of A_a, A_b, and A_c have been measured [9]. At most, A_b will be only about 0.1% of A_a during sliding. At low current densities A_c will be about 0.1% of A_b while at heavy overload it can approach the total load-bearing area. The minute conducting areas making up A_c are called "a-spots."

B. CONTACT RESISTANCE

Since the total conducting area is but a small percentage of the apparent area it is obvious that the majority of the lines of current

flow arriving at the contact will be bent in order to pass through an a-spot.

In the absence of a film, the contact resistance, R, is entirely due to the constriction of the lines of current flow. The more general case of different contact materials in the presence of a film can be represented by equation (3).

$$R = R_1 + R_2 + R_f \quad \text{ohms} \tag{3}$$

where R_1 and R_2 are the constriction resistances and R_f is the resistance of the film.

The constriction resistance can be roughly calculated by $\frac{\rho}{na}$ where ρ is the conductivity of the contact member, n the number of conducting spots, and a the radius of an average circular spot [10]. R_f is just the ratio of the resistance measured across one square centimeter of film to the conducting area.

C. CONDUCTION

It is well known that immediately following the cleaning of a base metal surface in air, a protective film begins to form. The nature of this film under various atmospheric conditions will receive close attention in Section III. For the present assume that a copper slip ring has been freshly machined. The thickness of the cuprous-oxide film which forms is a logarithmic function of time exposure to air at room temperature [11].

1. Tunnel Effect

Since CuO_2 is an n-type semiconductor it is reasonable to expect some solid-state nomenclature in the contact field. Such is the case for the well known tunnel effect. For film thicknesses of

less than 50 Å conduction across the contact is accomplished by tunneling [12]. However, since conduction has been measured through tarnish films several thousand angstroms in thickness, some other mechanism of conduction must exist.

2. Fritting

Evidence of a second method of conduction can be easily demonstrated in an experiment originally conducted by R. Holm in 1941 [13]. Consider a stationary contact containing a high-resistivity film of about 500 Å thickness. A voltage source is placed in series with a large current-controlling resistor and this contact. The voltage drop across the contact is measured with a potentiometer. If the current is now increased incrementally from zero a metallic contact characteristic will be noted; i.e., the contact will provide essentially ohmic resistance. However, when the electric field strength across the film reaches approximately 10^8 V/m (at about 5 volts contact drop) the film suddenly appears to puncture. The exact required voltage is dependent on film thickness and structure. The contact drop will now be on the order of 0.2 to 0.4 volts, independent of additional increases in applied voltage.

The process just described is known as A-fritting. A complete understanding of fritting is lacking, but can be outlined as follows [14]. The initial point at which film breakdown takes place is undoubtedly the location of a discontinuity in the film. This may be due to some impurity or just a thin region in the film with its associated higher conductance. Regardless of the cause, the result is a slight reduction in thickness of the boundary potential barrier. Electrons, therefore, have a higher probability of passage through the boundary.

The electrons thus injected into the film produce a strongly enhanced flow of current confined to a narrow path. Consequently, the contact material in this path is heated causing reduced cohesion of the film. The result is a channel through the film - an a-spot.

Once an a-spot has been established in a stationary contact, its size is determined by the applied voltage. This adaptation of the area of the spot to maintain a small voltage drop is called B-fritting. In a sliding contact each spot on the collector ring spends only a small percentage of each revolution beneath the brush. B-fritting and re-oxidation are in dynamic equilibrium in this case.

E. Holm [12, 15, 16] has done extensive research into evidence that the conduction process is not the same across anodic and cathodic brushes. (An anodic brush is here defined as that brush from which conventional current flows to the ring). Oscillograms of the contact voltages of electrographitic brushes riding a copper slip ring showed definite polarity effects after sliding only 10 km. The cathode voltage fluctuated rapidly between 0.4 and 1.0 volts. In contrast, the anodic brush drop remained almost steady at 0.4 volt. Tests were made with numerous initial film thicknesses, brush grades, current densities, spring pressures and ring materials. The polarity effect occurred with only slight variations in all cases.

E. Holm explained these results based on fritting theory. Under the cathodic brush oxidation seems to be rapid and continuous due to the availability of positive metal ions which have migrated through the oxide film. These ions combine with electrons in the a-spot to form a metal bridge. The relative motion of sliding shears the metal bridges providing clean, highly stressed metal which is rapidly oxidized when

exposed. Under equilibrium conditions, the formation of new bridges, which depends on a diffusion process, might be a relatively slow process. However, overvoltages of about 1.5 volts, in air, were available to speed the process.

The relatively steady anodic contact voltage indicated that the a-spots in this track were covered with a thin tunnel-conducting film which prevented rapid oxidation. In addition, the electric field across this contact is so oriented as to retard metal ion migration and bridge formation.

D. TEMPERATURE CONSIDERATIONS

The measurement or calculation of the exact temperature of the surface of a sliding contact is an understandably difficult task. R. Holm [17, 18] and Shobert [19] have provided rigorous analytic studies of several cases. For the purposes of this paper a summary of their results will suffice.

It must be realized that the carbon-copper contact is materially unsymmetric. Some of these differences are shown in Table 1.

TABLE I

Sample Material Constants at Room Temperature [19]

Material Constant	Copper	Graphite Brush
Thermal Conductivity (W/m°K)	380	30
Thermal Capacity (10^6 J/m^3)	3.4	1.5
Resistivity (10^{-8} Ω-m)	1.8	4500
Hardness (10^8 N/m^3)	5	2

Due to the high resistivity of the carbon, the warmest isotherm is located slightly within the brush. One source of heat at the contact

is friction. Its generation is uniform over the load-bearing area and because of the thermal gradient between the brush and ring, this heat flows directly into the ring.

Joule heating must also be regarded but its exact flow path is less predictable. Consideration of the thermal gradient alone would indicate that about one-half the I^2R heat from the brush flows through the a-spots to the ring. However, since the friction heating of the contact alters the thermal gradient it is estimated that only about one-quarter of this heat reaches the ring.

Shobert [20] has applied R. Holm's heat-flow equations and graphs to obtain estimates of maximum temperatures in various machines. In all cases these calculated temperatures were harmless, being well below even the softening temperature of the ring in most cases. This result may sound trivial, but much of the early literature dealing with conduction theory hypothesized that, in the a-spots, the ring material melted and flowed thus providing a small conducting whisker through which current passed. Since the melting temperature of copper is 1083°C and Shobert's highest continuous-duty copper ring temperature was 157°C, it is not difficult to see why this phase of fritting theory has been abandoned.

E. FRICTION AND WEAR

1. Friction

In Section II A, it was shown that only about 0.1% of the apparent contact surface area was mechanically loaded during sliding. Considering this area, A_b, the coefficient of friction, μ, is defined as:

$$\mu = \frac{F}{P} \tag{3}$$

where F is the tangential friction force. As indicated by R. Holm [21],

$$F = \quad A_b \text{ grams} \tag{4}$$

where is the shearing strength of the film for smooth sliding. Combining equations (1), (2), and (4), yields:

$$= \quad = \quad \tag{5}$$

At the start of sliding k = 1. During seating, k decreases and A_b increases, leaving about constant. Therefore, increases in proportion to the load-bearing area. Typical values for collector friction phenomena are $0.01 < \quad < 1.0$ and between 0.1×10^6 and 0.2×10^6 gr/sq cm.

The great usefulness of carbon as a contact material stems from the well known variation of its cohesive binding forces within the crystal lattice. In the hexagonal 001 and 002 planes each carbon atom is bound to its three nearest neighbors by convalent bonds of 3.5 eV per atom pair [22]. The forces in quadrature with this basal plane are relatively weak, having been measured at about 0.25 eV in a perfect crystal [23]. Lattice defects further reduce these forces thus accounting for the natural lubricity of carbon.

Unfortunately this natural low-friction operation of carbon is dependent on the environment in which it is operated, as well as the actual contact surface. This can be seen in equation (5). Without either sufficient humidity or organic vapors even graphite against graphite will suffer the catastrophic wear known as dusting. Due to this dependence of friction on the film, experimental data which presents friction measurements must be examined with great care. The presence of oil vapors, tobacco smoke, or even seasonal changes in relative humidity can affect the results obtained.

Possibily because meaningful friction measurements are so difficult to obtain and because the friction coefficient itself is not an accurate indication of brush performance many investigators avoid this problem by directly monitoring wear.

2. Wear

Contact wear is generally defined as the decrease in brush length divided by the distance traveled. If peripheral speed is constant, a more useful definition is the change in length with time of operation, from which a wear rate can be easily determined.

One of the first complete analyses of slip-ring films was made by Van Brunt and Savage in 1937 [24]. The film was stripped from the track of a copper ring after extended running under electrographitic brushes at heavy load. Starting at the ring the analysis showed the film structure to be as follows: 2.1×10^{-6} -cm thickness of Cu_2O, 3.3×10^{-6} -cm of carbon, and finally a discontinuous layer of residue containing SiO_2, Al_2O, Fe_2O_3, and CaO.

As with contact conduction, several brush-wear theories have been proposed. Although not in conflict these theories tend to place emphasis on different aspects of the problem. Wear between carbon contacts or between a brush and a precious metal is largely independent of the current and dependent on the mechanical loads alone. However, wear of carbon brushes on an oxidizing ring such as copper shows decided dependence on current and variation with brush polarity [25]. In general it was found that the cathodic brush wore from two to four times faster than the anodic when they were run on separate tracks.

E. Holm [15] confirmed these results and proposed a theory of electrical wear based on the polarity effect. As described previously, under the

cathodic brush the process of fritting, breaking of metallic filaments, and oxidation goes on continuously. Although only a small amount of copper is transported, this process seems to be the source for the formation of cuprous oxide. This also accounts for the roughening of the cathode track. Copper particles with carbon attached were found embedded in the cathodic brush face and in wear debris. These grains, after work hardening, could easily abrade the brush.

Under the anodic brush metallic filaments cannot form. The thin film covering the a-spots prevents rapid oxidization and only slight wear is experienced. This theory falls into the general class of adhesive wear since it depends on strong chemical bonds between respective contact members without dependence on the mechanical interlocking of protrusions.

British investigators have supported the adhesive wear theory but have extended it slightly [26]. The actual mechanism of partical removal is thought to be a fatigue process, on the microscopic scale, resulting from a succession of repeated elastic stresses over the localized regions of true contact.

III. ATMOSPHERIC EFFECTS

Atmospheric effects are felt in their influence on the coefficient of friction and on the conduction of current through the sliding contact. They result in changes in operating temperature, wear rate of brushes and rings, and quality of commutation.

Baker [27, 28] was one of the earliest investigators to recognize the importance of atmospheric conditions in collector operation. He concluded that the normal protective oxide film formed on copper rings accounted for the electrical characteristics of ordinary sliding contacts.

A. HUMIDITY

Many studies of the effect of humidity on contacts have been made. The usual concern has been unsatisfactory performance in the absence of sufficient water vapor.

The very dry polar air masses which invade the northern United States during the winter months have caused rapid brush wear in power stations. Braken [29] reported that adding moisture to the ventilating air around the sliding contacts in these stations controlled the problem. Dobson [30] was the first to duplicate these conditions in the laboratory and establish the critical moisture level as about two grains per cubic foot.

The humidity problem became critical during World War II when aircraft began flying above 20,000 feet. In as little as one hour new brushes were being completely worn out. Meteorological data indicates that the absolute humidity is a rapidly decreasing function of altitude. At 20,000 feet only about 0.25 g/ft^3 of water vapor is available [31].

A wide variety of solutions to this problem were advanced. Elsey [32] suggested that water vapor did not function as a boundary lubricant but rather as a catalyst in the formation of cuprous oxide. He patented the idea of adding metallic halides, now called adjuvants, to aircraft brushes, thus eliminating the need for atmospheric moisture. Elsey's theory of catalytic action seemed reasonable since films from these treated brushes closely resembled normal sea-level cuprous-oxide films in both appearance and performance.

Another water-vapor theory was proposed by Savage [33]. He suggested that a monomolecular layer of absorbed water on both the brush and film carbon serves to satisfy the free surface valences of this carbon. Without this cancellation these forces will cause adhesive wear. Other materials such as metallic halides might therefore be used in place of water to eliminate these surface valences.

Regardless of the exact mechanism by which water is utilized, its presence or a suitable substitute is essential to the long life and proper performance of sliding carbon contacts. Figure 1 is included to show the relative humidity and temperature effects since absolute humidity is a rather esoteric term.

Pardee [35] looked into the effects of water vapor on silver-graphite brush performance in pure atmospheres of nitrogen, carbon dioxide, helium and air. His results reinforce Savage's wear theory. The amount of water vapor required to prevent dusting in nitrogen, in helium, and in air was found to be inversly proportional to the ease with which each gas was absorbed at carbon lattice sites. Operation in carbon dioxide was found to be independent of water vapor. It was thought that carbon dioxide acted in a manner similar to oxygen in air, i.e., by increasing

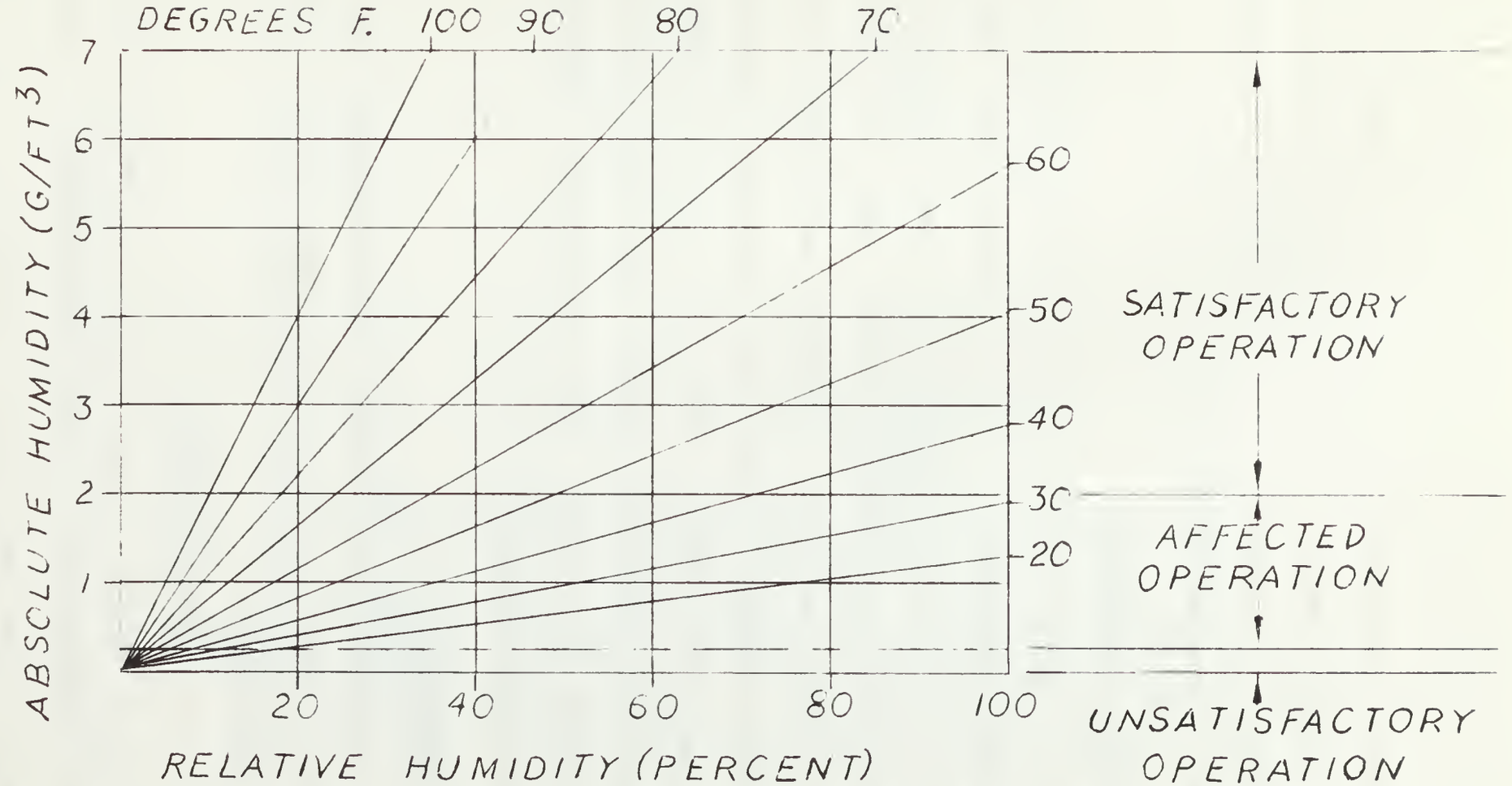

Figure 1. Relation Between Brush Wear Rate and Humidity Based on the Usually Accepted Minimum Value of 2 g/ft^3 [34]

the attractiveness of graphite toward water vapor [36]. The minimum absolute humidity reported by Pardee for air was less than one one-hundredth of the generally accepted value of two grains per cubic foot. This is another example of the interdependence of contact phenomena and was explained by variations in brush compositions, sliding speeds, spring pressures and current densities.

B. UNUSUAL ENVIRONMENTS

In the search for more predictable brush performance the question of possible operation in pure gasses has been studied. Baker and Hewitt [37, 38] checked the wear rates of 80-20 copper-graphite brushes against copper rings in air, hydrogen, nitrogen, oxygen, and carbon dioxide. Sufficient water vapor was introduced to avoid dusting. Figure 2 shows the results obtained. The low rates of brush wear in hydrogen have proven useful when applied to the design of hydrogen-cooled ac turbo-generators and synchronous condensers. When dryness and associated unsatisfactory wear occurred in some of these units, high-altitude halide-treated brushes corrected the situation [39].

C. CONTAMINATION

In contrast to the beneficial effect of hydrogen, minute quantities of several common vapors have proven to have disastrous effects on collector performance.

1. Hydrogen Sulfide

Since it occurs frequently in industrial plant atmospheres, hydrogen sulfide is one of the most universal of the troublesome contaminats. When commutating difficulties occur in the heavy-duty dc machinery of steel mills, chemical plants, or paper mills, hydrogen

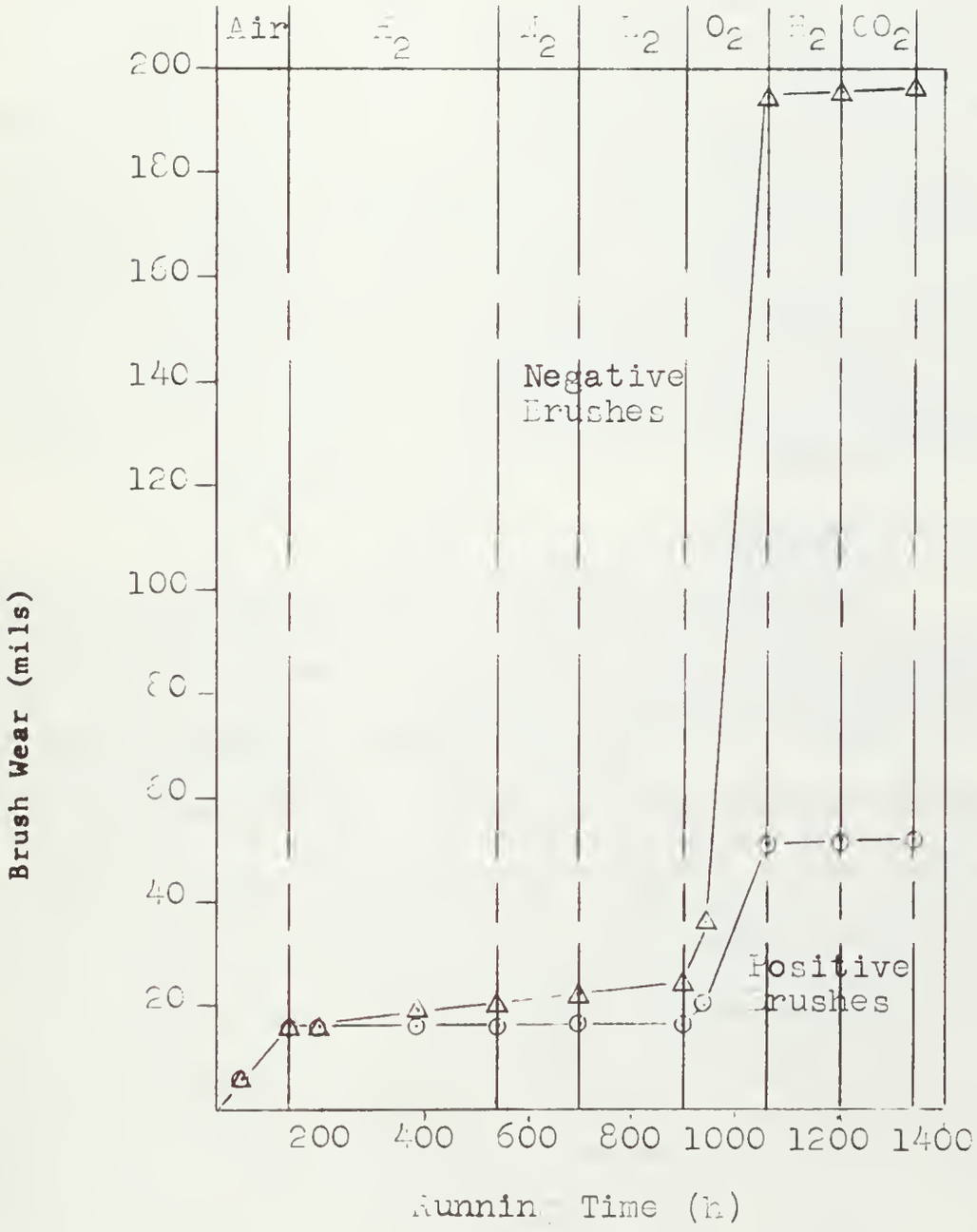

Figure 2. Wear Curves of 80-20 Copper-Graphite Brushes in Various Gases [38]

sulfide is immediately suspect. This contaminant can usually be recognized by the appearance of gray copper-sulfide films which form on exposed copper surfaces. Extended operation in the presence of sufficient concentrations of hydrogen sulfide will cause sever brush wear, commutator threading and grooving, and poor commutation [40]. Moberly [41] has investigated H_2S contamination and found that concentrations as low as 6 ppm resulted in film damage. He outlines the following theory by which this situation may develop. Since H_2S is a highly reactive gas it has a greater affinity for copper than does oxygen. The resulting porous, weakly bonded film continues to grow as more H_2S diffuses to the copper surface. This film is easily abraded, exposing the commutator to further damage.

2. Silicone

Commutation difficulties during World War II were by no means limited to high-altitude aircraft. A common fleet problem, the need for increased power without significant increase in weight or space, was being investigated by industry. Machine designers had met this challenge with a silicone-insulated double-armature dc motor which produced about 40% greater rated output in the same weight and space [39]. This unit surpassed all specifications when operated as an open machine. However, when the motor was totally enclosed and cooled by recirculating air, poor commutation and high brush-wear rates soon developed. Laboratory tests indicated that the cause was silicone (methyl polysiloxane) vapor contamination from the hot silicone insulation. Concentrations as low as 0.1 ppm have caused increased brush wear [42]. Increased curing of these silicone insulating materials had little beneficial effect. Even following excessive curing most types

of silicone continue to yield thermally dissociated vapors of low molecular weight.

Several theories for this rapid wear have been suggested over the years but probably the most intensive research has been conducted at the Naval Applied Science Laboratory [43]. Katzenstein attributes the high wear rate to the combination of siloxane-vapor-catalysed oxidation of carbon at the brush face and a continuous stripping of the resulting rapidly formed, high-strength film. Although several patented adjuvants have provided some control over this problem, latest available information indicates that the use of silicone derivatives in Class H-insulated totally enclosed shipboard motors is still prohibited.

3. Carbonaceous Vapors

A final troublesome group of contaminates are the heavy organic vapors which are present in high concentrations near industrial plants. These include lubricating oil, grease, paraffin, pitch and tar from coking ovens, and even tobacco smoke.

Evidence of this type of contaminant is a thick dark film which may resemble a varnish coating [40]. Lynn and Elsey [39] pointed out that copper acts as a catalyst in the formation of sludge in transformer oils when exposed to air. A hot commutator may serve in the same capacity thereby converting hydrocarbon vapors into resinous solids. These deposits are then thermally decomposed leaving the varnish film observed. This problem has been partially solved by using a series of slightly abrasive electrographitic brushes [44].

IV. EXPERIMENTAL APPARATUS AND PROCEDURE

A. SUBMARINE ENVIRONMENT

In order to provide additional evidence to support the hypothesis that the atmospheres aboard nuclear submarines are contributing to collector difficulties, it was necessary to obtain an analysis of these environments. This information is provided in Ref. 45 in which the quantitative identification of seventy nuclear submarine atmospheric contaminants is discussed. Maximum permissible concentrations have been established for only thirty of these constituents. Since this report was oriented toward physiological atmospheric safety one-hour, twenty-four hour, and ninety-day exposure limits are provided. For continuous machine operation only the ninety-day limit is pertinent. The thirty limited compounds and their ninety-day limits appear in Table 2.

Ten of these compounds were eliminated from consideration for various reasons. Testing was considered too dangerous with arsine, phosgene and stibine which are powerful poisons. The effects of carbon dioxide, hydrogen, oxygen and ozone have been studied and found to be negligible in the presence of sufficient water vapor. Finally, the limits on hydrocarbon solvents, mercury, and triaryl phosphate are less than 0.5 parts per billion and therefore considered harmless. Of the remaining twenty contaminants which were thought to be harmful, time permitted testing of only eight.

B. EXPERIMENTAL APPARATUS

1. General Description

Figure 3 shows the test unit which was constructed to examine

TABLE 2

Limits for Atmospheric Constituents in Nuclear Submarines (Limits in ppm by Volume Unless Otherwise Noted)

Chemical Substance	90-Day Limit
Acetone	300
Acetylene	6000
Ammonia	25
Arsine	0.01
Benzene	1.0
Carbon Dioxide	3.8 mm Hg
Carbon Monoxide	25
Chlorine	0.1
Freon-12	200
Freon-114	200
Ethanol	100
Hydrocarbon Solvents	73 mg/m^3
Hydrogen	10,000
Hydrogen Chloride	1.0
Hydrogen Floride	0.1
Isopropanol	50
Mercury	0.01 mg/m^3
Methane	13,000
Methanol	10
Methyl Chloroform	2.5
Monoethanolamine	0.5
Nitrogen Dioxide	0.5
Oxygen	140-160 mm Hg
Ozone	0.02
Phosgene	0.05
Stibine	0.01
Sulfur Dioxide	1.0
Triaryl Phosphate	1.0 mg/m^3
Freon-11	5
Vinylidene Chloride	2

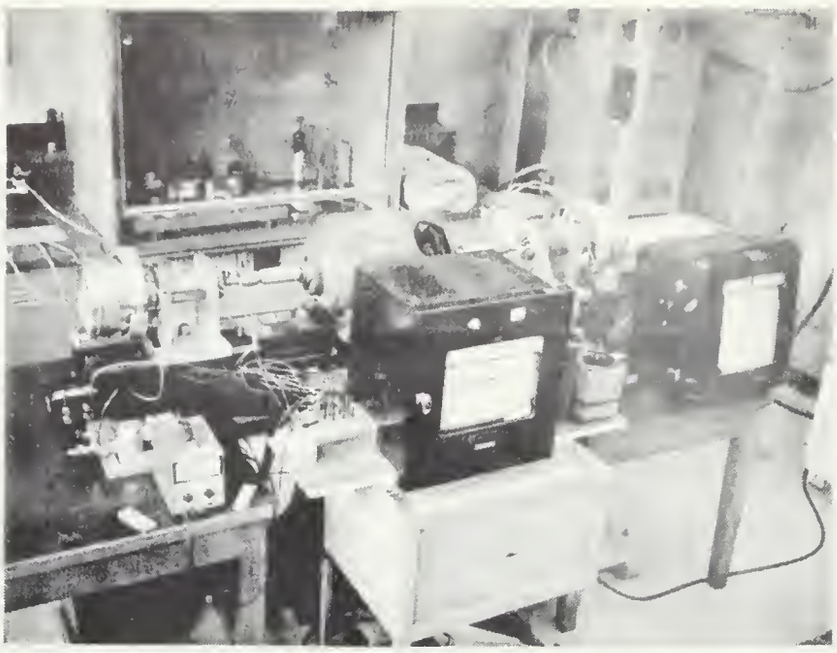

Figure 3. Brush Wear Testing Apparatus

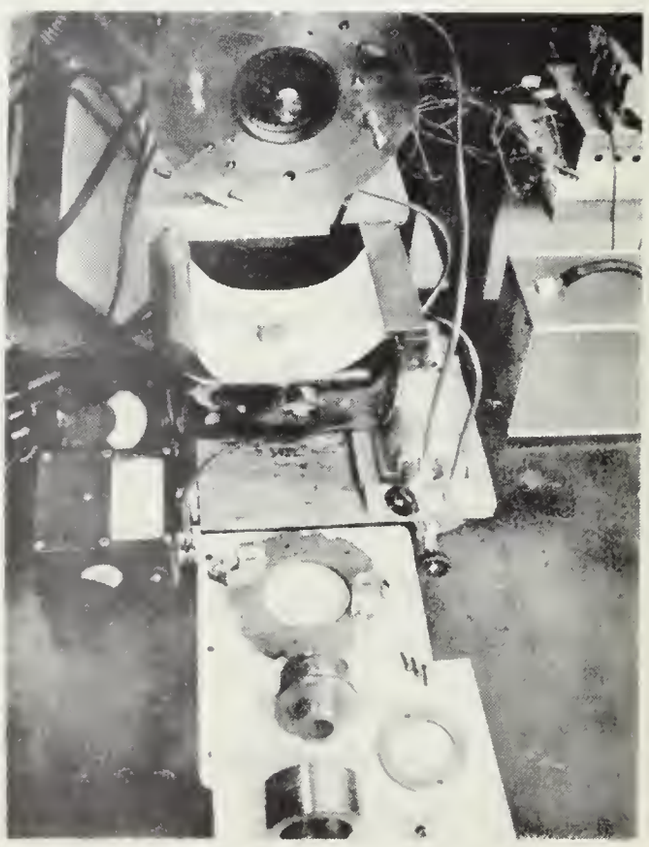

Figure 4. Disassembled Chamber showing Brush-holders, Carbon Sleeves and Helically rooved Slip Ring

the effects of atmospheric contamination. The major components of this unit were: (1) a 5-hp dc motor with associated Thymotrol drive, (2) two stainless-steel test chambers which enclosed the brushes and rings, (3) electrical loading circuits, (4) atmospheric control and circulating systems, and (5) various recording equipment.

This test unit was designed to correlate as closely as possible with the troublesome units in the fleet. According to the technical manual for the 30/10-KW motor generator sets [46] grade 258 National Carbon brushes riding eight-inch diameter Allis Chalmers alloy #13 slip rings are the elements of the ac generator collectors. Alloy #13 has the following composition: 86.0 to 89.0% copper, 9.5 to 10.5% tin, and 1.5 to 3% zinc. Full-load brush current density is 16.3 A/in^2 in the 32.4-KW generator and 10.1 A/in^2 in the 10.8-KW generator. These units, mounted on a common shaft, are turned at 1714 rpm by a 75-hp dc motor.

In the test unit the electrical load circuits provided 60-cycle, single-phase, full-wave rectified current to the brushes. Input voltage was maintained at 5 volts and power was dissipated across a carbon pile. A current density of 50 A/in^2 was used for all brush wear tests since the low densities used in the MG sets could introduce high friction and wear due to overbrushing.

Brushholders for these tests were provided through the courtesy of Mr. George H. Gunnoe of General Electric Company who had used them successfully in previous experiments. As seen in Figure 4 these holders are of a recent design which incorporates a Class I constant-force brush spring [47]. The use of this helically wound spring essentially eliminates variation of spring force with brush length.

National Carbon grade 258 electrographitic brushes were used in all tests. The specifications for these brushes were as follows: 1-3/8 inches long, 3/4 inch wide, 3/8 inch thick, 30-degree top bevel, 20-degree bottom bevel, with "Q" type cemented shunt connection. A small hole was bored diagonally from the top of each brush to within 1/4 inch of the new brush face. A ten-mil copper-constantan thermocouple junction was cemented into each hole using high-temperature, electrically insulating cement. The second junction of each thermocouple was held at 0°C in a Dewar flask containing melting ice.

2. Test Chambers

One of the most critical features in the experimental apparatus were the test chambers which surrounded the collectors. To insure that a satisfactory seal was maintained around the rotating shaft, these units were built using Westinghouse Research Laboratory drawing 32-A-3637. Chambers built to these specifications have been successfully used for various simulated high-altitude tests over the past eighteen years. Since the simulated submarine environmental tests would be run at ambient pressure it was thought that these chambers would be more than adequate to insure against leakage. A detailed description of these chambers including diagrams is contained in Ref. 41. Figures 3 and 4 show the chambers assembled and disassembled. Basically, the chambers consisted of a nine-inch diameter stainless plate through which were brought the drive shaft, insulated brushings for load current and thermocouple leads, and inlet and outlet ports for the contaminated air. The shaft seal consisted of two very close tolerance carbon sleeves. The brushholders were mounted on an annular ring made of glass-reinforced phenolic laminate. A helical groove with a pitch of 1/4 inch and a

width of 1/32 inch was cut in each slip ring since Elsey, et al. [41] had experienced burned or flat spots after two days of testing on rings which didn't have this groove. Figure 4 shows these features.

A cylindrical stainless-steel cover containing a glass viewing port completed the chamber. The copper tubing wrapped on this cover carried cooling water. This heat exchanger was added after initial tests indicated that a reasonable chamber temperature could not be maintained by convection alone. With this added feature, the chamber temperature was maintained at about 65°C for all tests.

3. Atmospheric System

The remainder of the endironmental control system is shown in Figures 5 and 6. Included were a diaphragm pump, flow meter, removable stainless reservoir, injection port with self-sealing septum, and various valves and copper tubing to complete the closed system. The 20-liter reservoir was used to increase the system volume for those cases in which very small amounts of contaminant were needed. Teflon gaskets and teflon tape were used for seals throughout the system to minimize absorption or contamination from rubber sealing material.

Figure 6 pictures the air filtering and humidifying equipment. The filter consisted of two 20-micron mechanical filters and a one-foot column of activated charcoal powder. The second filter which followed the charcoal was used to keep the powder from entering the system. To insure that sufficient water vapor was present to avoid brush dusting, but not enough to produce condensation anywhere in the system, a bubble tower was used. This column was bathed in a large beaker of water at 10°C during atmospheric processing. Saturated air at 10°C and ambient pressure will contain about 4.1 g/ft^3 of water vapor and should serve

Figure 5. Atmospheric control and circulating system

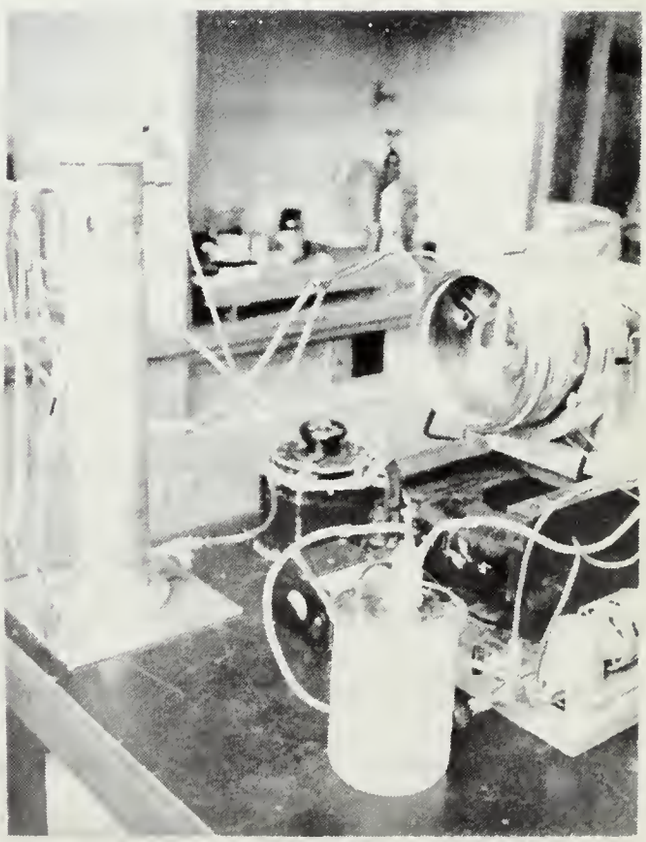

Figure 6. Air filtering and humidifying equipment

both purposes mentioned above. Saturation was assumed since the bubble tower contained a fritted glass filter which broke the air into fine bubbles greatly increasing the exposed surface area. No condensation was observed during any test in which the 10°C bath temperature was used.

4. Recording Equipment

Brush temperatures and contact voltages were recorded on the two six-point recorders shown in Figure 3. The maximum scale reading on either recorder was twenty millivolts. Since contact drops of up to two volts were expected, these voltages were first passed through a precision 200-to-1 voltage divider.

Figures 7 and 8 show the jig which was built to provide accurate brush wear measurements. With reasonable care differences of 0.1 mil could be easily duplicated with this unit.

C. TEST PROCEDURE

1. Brush Wear Tests

The following rest procedure was used in taking the wear data displayed in Section V and Appendix A.

a. With the motor turning at 1800 rpm the brush and ring surfaces were cleaned by lightly applying a medium grade brush-seating stone to the ring. The collector was then blown-out and wiped free of carbon dust and stone residue. With the chamber covers off, the unit was brought up to speed (4,220 rpm) and the electrical load (50 $A.in^2$) applied to the brushes.

b. Following a filming run of three hours duration, the unit was stopped. The brushes were removed from the holders, checked for proper seating and allowed to cool. The measuring jig was then used to make three initial equidistant brush length measurements across the

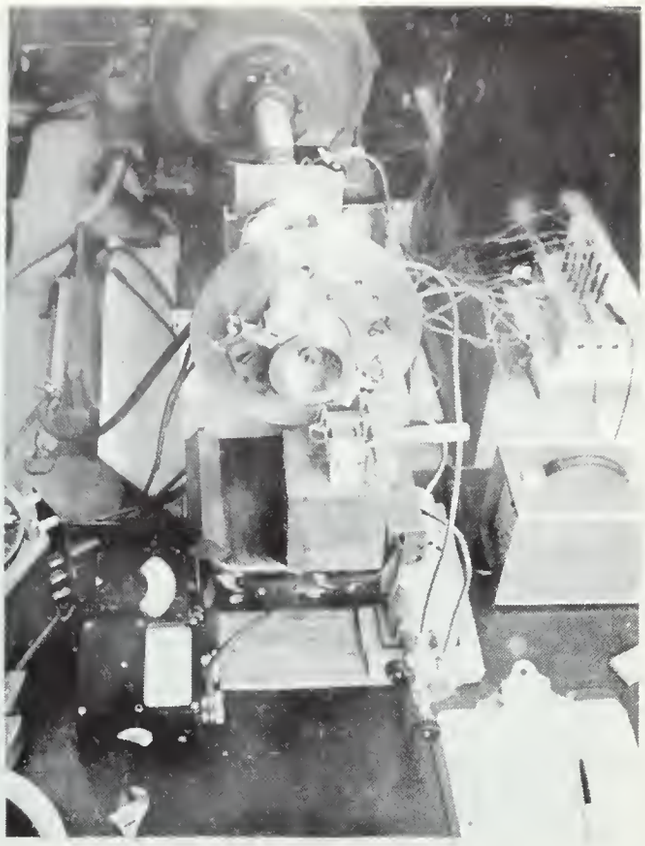

Figure 7. Brush Wear Measurement in Progress

Figure 8. Close-up of Brush Wear Measuring Jig

brush width. This procedure is depicted in Figure 7.

c. After again blowing-out the accumulated carbon dust, the brushes were reinserted and the chambers closed. The charcoal tower was next installed using rubber hose. Fresh air from outside the laboratory was drawn through the filter into the environmental system and exhausted. With the reservoir in place the system volume was about 23 liters. Pump capacity was only 2 liters per minute. To insure that the entire system was purged, filtered air was drawn for at least 15 minutes.

d. The system was then isolated and the filter column removed. The bubble tower was then placed in the system and the previously filtered air humidified for 15 minutes.

e. The system was then isolated once again and the motor brought up to test speed. The petcock containing the self-sealing septum was then opened and the proper amount of contaminant injected with a syringe. At this point the electrical load was applied, the recorders were started and the cooling water cut-in.

f. After twenty-four hours of running at load the unit was stopped and allowed to cool. The covers were removed and brush wear measurements taken. Steps (c) through (e) were then repeated. Note that the film was not altered at this point.

g. At the end of the second day of testing, a chamber air sample was drawn using the technique employed in medicine to take blood samples. Examples of the commercially evacuated test tubes and double-needle actuators used in this process appear at the bottom of Figure 9. Just prior to stopping each test, the load current was incremented to provide data for the contact-drop versus current-density curves of Section V.

Figure 9. Contaminant, Input and Sampling Apparatus

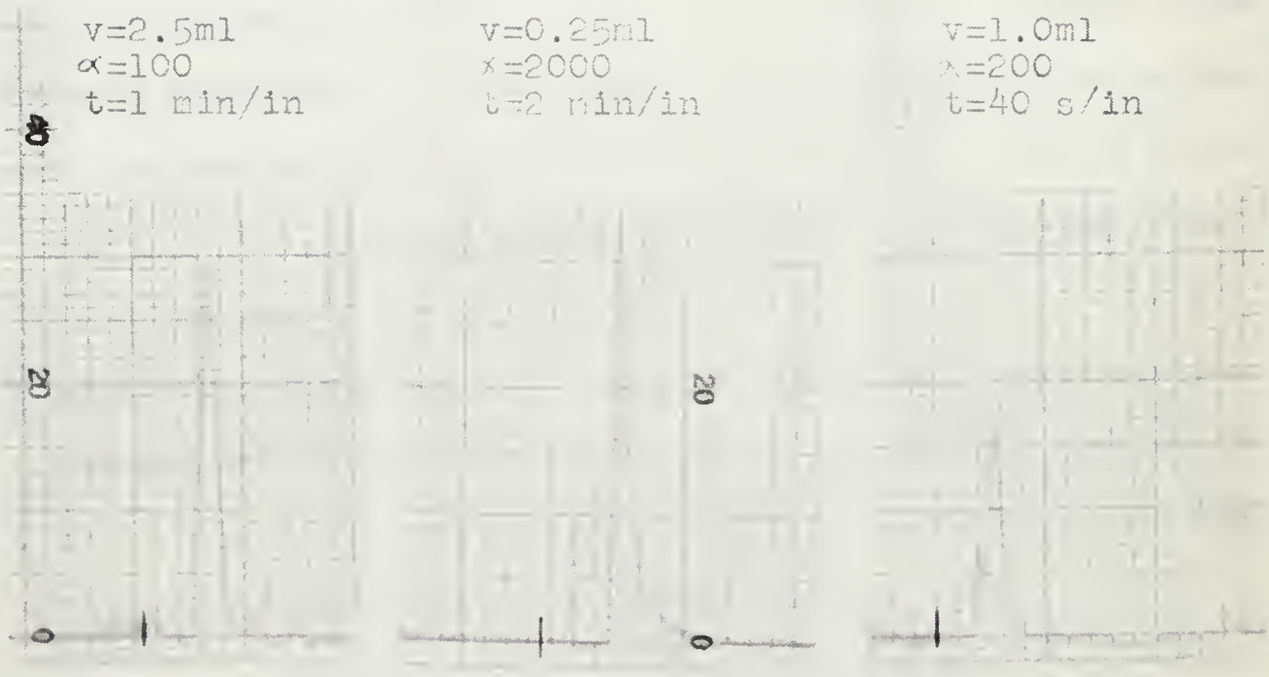

Figure 10. Chromatograms for Uncontaminated Air, Acetone Standard, and Acetone Contaminated Chamber Sample Note that v = Input Volume, × = Attenuation and t = Time Scale.

2. Gas Chromatograph Tests

In an attempt to find the amount of contaminant remaining in the system at the end of each test, the samples drawn were tested in a gas chromatograph using columns containing 5% Carbowax 20M and 30/60 Chromosorb. Flame ionization detection was used for increased sensitivity.

The following procedure was used in this phase of testing.

a. Evacuated containers were weighed before and after a pure contaminant was admitted to each. From the weight difference and the known molecular weight of each contaminant, the number of moles contained in each of these "standards" was determined. By use of the ideal gas law, the pressure within these standard vials was then found.

b. Small amounts drawn from these standard containers and from the corresponding chamber samples were then passed through the chromatograph to obtain an area ratio from the chromatograms which resulted.

c. Multiplying this area (including associated attenuation factors and sample sizes) by the pressure determined in step (b) yielded the volume ratio of contaminant to air.

A sample problem is included to clarify the above outlined procedure. The contaminant was acetone which had a retention time of 44 seconds. (Retention time is the time delay between sample injection and the appearance of a peak on the chromatogram). The weight of pure acteone drawn was 1.15×10^{-2} grams.

$$n \text{ (number of moles)} = \frac{\text{weight}}{\text{molecular weight}} \qquad (6)$$

$$= \frac{1.15 \times 10^{-2}}{58.08} = 1.96 \times 10^{-4}$$

Now let p equal the vial pressure in atmospheres, V equal the vial volume (5×10^{-3} liters), R be the universal gas constant (.0802 $\frac{\text{liter-atm}}{\text{mole-°K}}$) and T equal room temperature (293.15°K). The ideal gas law,

$$pV = nRT \tag{7}$$

yields a vial pressure of 0.944 atmospheres.

Figure 10 shows chromatograms for an uncontaminated chamber air sample, for the acetone standard, and for the acetone-contaminated chamber air.

Now the area ratio can be computed as follows:

$$\text{Area Ratio} = \frac{\left(A_2\right), V_1 \, , \, 2)}{\left(A_1\right), V_2 \, (\, 1)} \tag{8}$$

where A is the chromatogram peak area, V is the sample size, and α is the attenuation factor. Subscript 1 designates standard data and subscript 2 indicates chamber information. The data shown in Figure 10 yields an area ratio of 3.16×10^{-4}.

Finally, assuming a pressure of one atmosphere in the chamber sample yields:

$$\begin{aligned} \text{Volume Ratio} &= p \times \text{Area Ratio} \\ &= 0.944 \times 3.16 \times 10^{-4} \\ &= 299 \text{ ppm} \end{aligned} \tag{9}$$

which compares favorably with the input value of 300 ppm.

V. SUMMARY AND CONCLUSIONS

A. SUMMARY OF RESULTS

Tables 3 and 4 summarize the chromatographic and brush wear data obtained using the test procedures of Section IV.

TABLE 3

Chromatographic Test Results

Contaminant	Chemical Formula	Retention Time (s)	Input Volume (ppm)	Volume Found (ppm)
Acetone	CH_3COCH_3	44	300	299
Acetylene	C_2H_2	14	6000	38.6
Ammonia	NH_3	10	25	0
Freon-12	Cl_2CF_2	16	200	180
Freon-114	Cl_2CFCF_3	20	200	62.9
Hydrogen Chloride	HCL	30	1	0
Methane	CH_4	13	13000	91
None	-	17	-	-
Sulfur Dioxide	SO_2	12	1	0

These results were not particularly satisfying. The input volumes of the more volatile contaminants were badly depleted by the end of the 24-hour tests. Since brush dust has the very absorbent characteristics of activated charcoal, it is highly possible that these gases were removed by this dust. However, the possibility that leakage occurred cannot be ignored.

The peak observed for supposedly uncontaminated air was diagnosed as thermally liberated resin vapors from the annular phenolic ring which supported the brushholders. Though certainly undesirable, this background vapor was present in all chamber samples and its relative effects

can, therefore, be ignored. Replacement of these rings with rings made from an inert material should eliminate this problem. Table 4 is a summary of the test data which appears in Appendix A.

TABLE 4

Brush Wear Test Results

Contaminant	Total Brush Wear (mils) Pos. Brush	Neg. Brush	Maximum Wear Rate (mils/day) Pos. Brush	Neg. Brush	Brush Temperature	Contact Voltage Data
None	2.80	2.86	1.90	2.13	Steady	Steady
Hydrogen Chloride	10.66	12.00	5.56	7.60	Very erratic	Very erratic
Methane	9.21	7.21	5.13	3.71	Erratic	Steady
Acetone	7.41	5.30	5.34	3.77	Steady	Steady
Acetylene	6.24	6.13	3.27	3.73	Very erratic	Steady
Freon-12	5.92	4.72	3.60	2.50	Steady	Steady
Freon-114	4.30	5.67	2.30	3.33	Erratic	Steady
Sulfur Dioxide	4.40	4.33	2.30	2.43	Steady	Erratic
Ammonia	4.14	3.96	2.50	2.40	Steady	Steady

B. CONCLUSIONS

It is always dangerous to try to draw conclusions from a small amount of data. However, several points can be made with reference to the original purpose of this study. The low wear rate for the uncontaminated case, 2.0 mils/24 h (4.1×10^{-7} cm/km of sliding) compares well with Shobert's data, Figure 11, in which best power brushes are shown to wear at about 6.0×10^{-7} cm/km [48]. Even the worst case, the wear rate of hydrogen chloride, was only about 6.0 mils/24h (1.05×10^{-6} cm/km). This rate is seen to be less than that of aircraft brushes at sea level, which is the next higher rate shown.

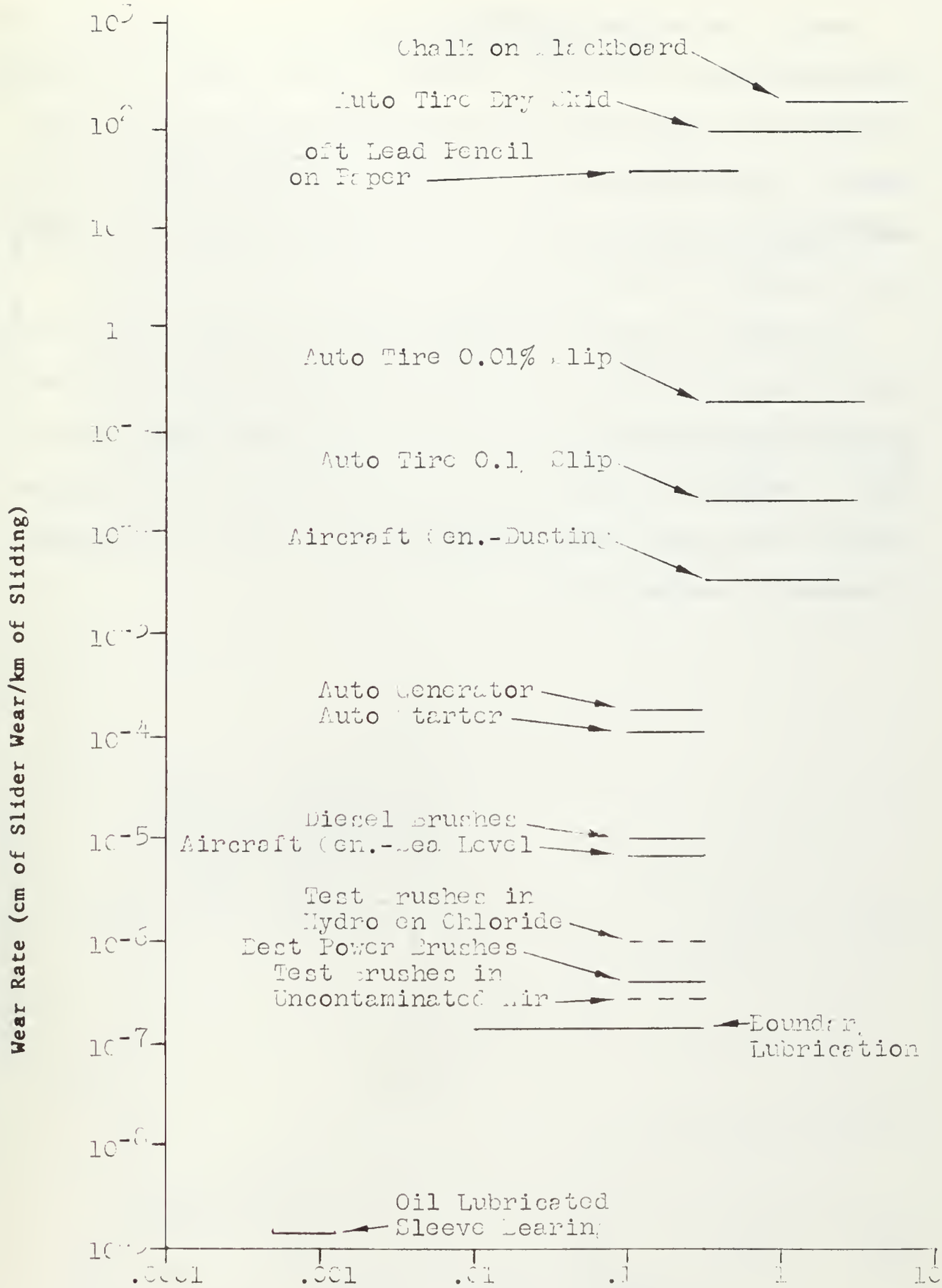

Figure 11. Comparison of Experimental Brush Wear Rates with Rates for Various Applications

However, the decrease in brush life by a factor of three, which has been demonstrated in the case of hydrogen chloride, cannot be discounted. Although no ring deterioration was observed during these tests, such a condition could develop during longer runs. The added down-time due to rapid brush wear coupled with ring or commutator threading could prove to be critical.

In summary, no single contaminant was shown to cause drastic brush wear or ring deterioration. The survey information together with the increased brush wear rate observed in these tests does suggest that in order to completely solve the difficulties being experienced in nuclear submarine motor generators, consideration must be given to the effects of atmospheric contamination.

APPENDIX A
BRUSH WEAR TEST DATA

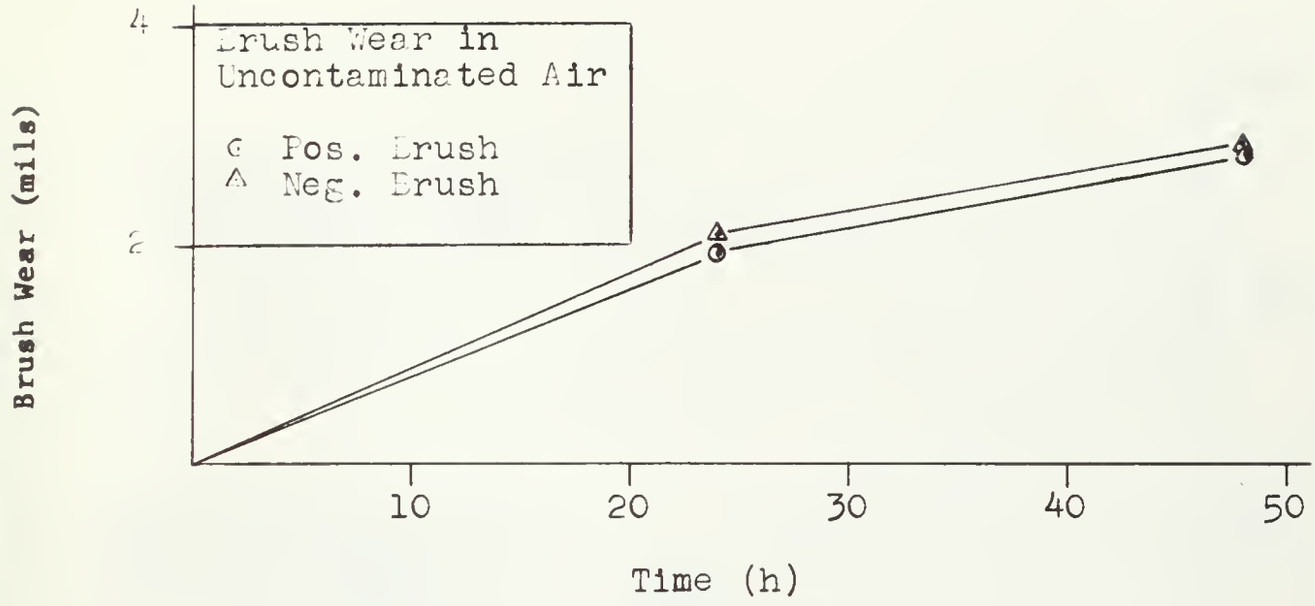

Figure 12A.

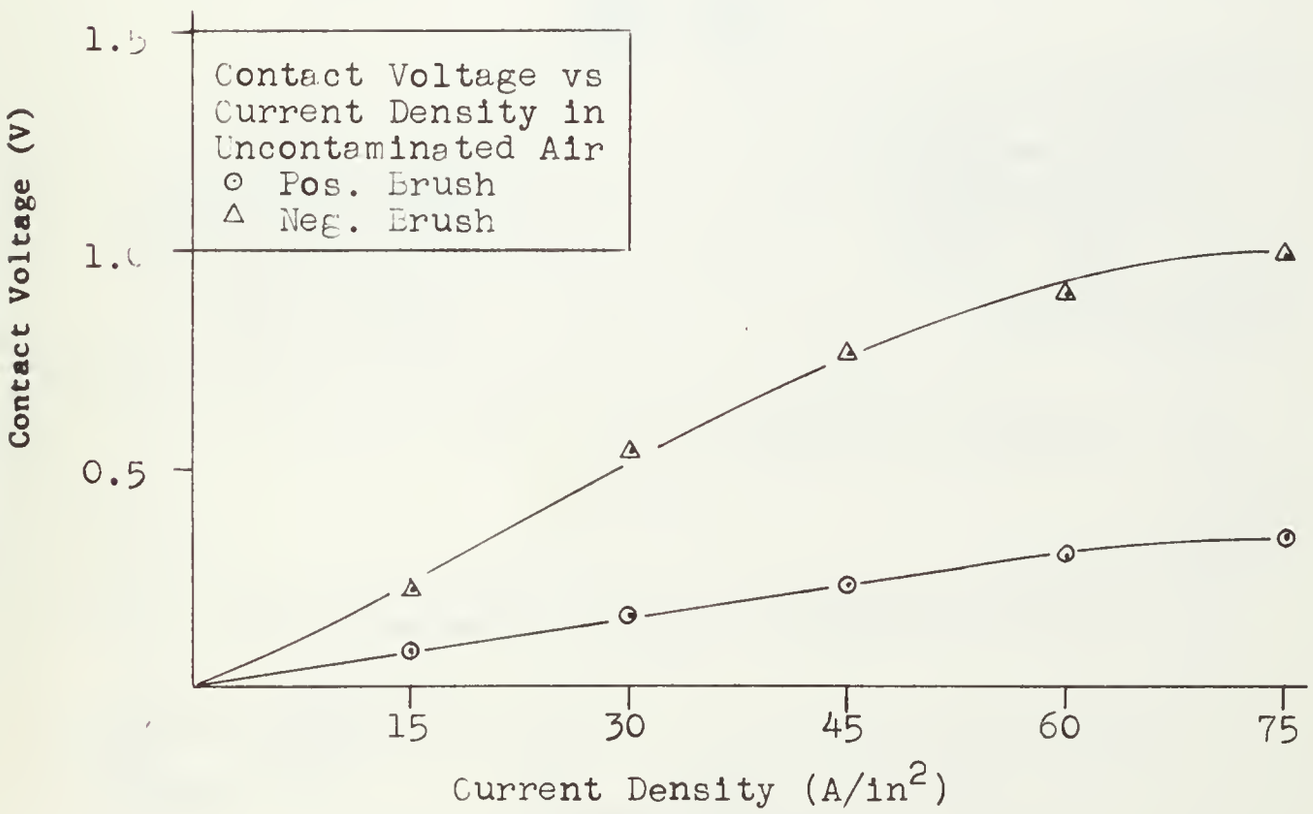

Figure 12B.

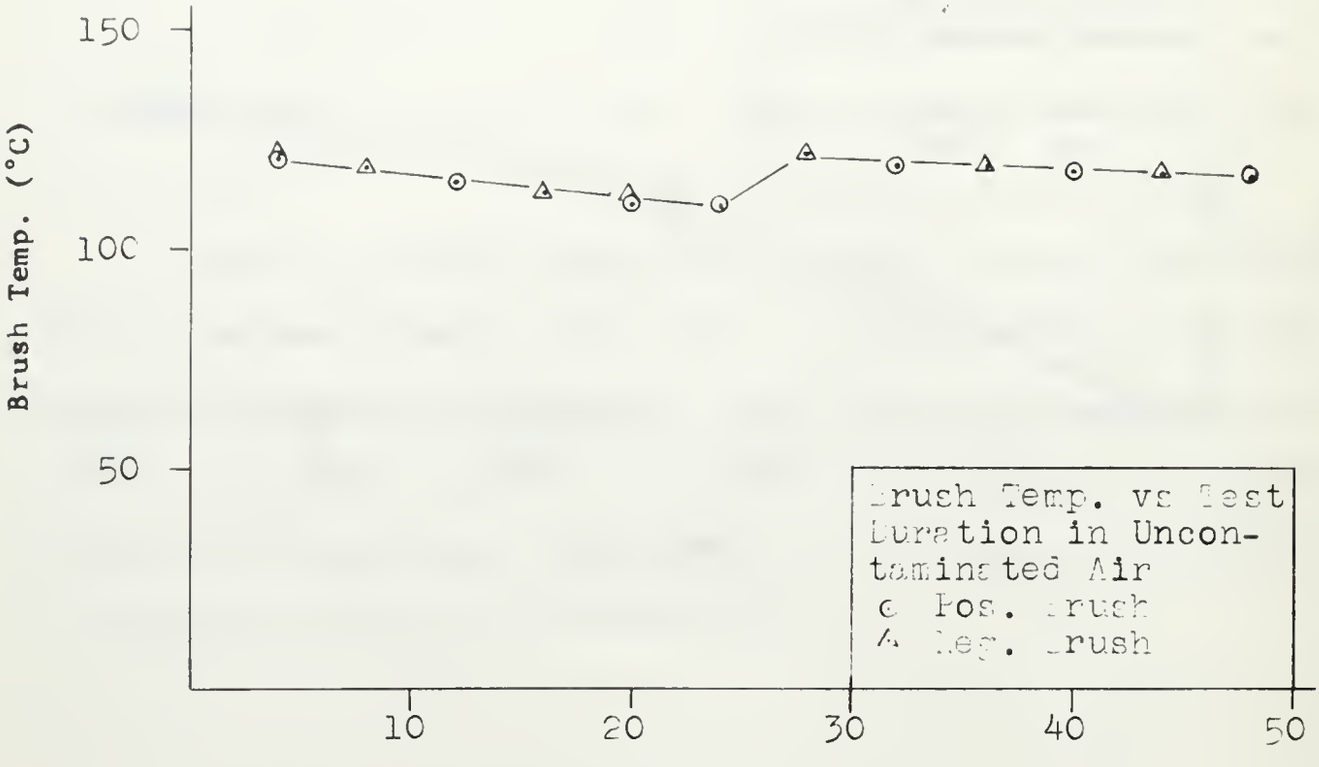

Figure 12K.

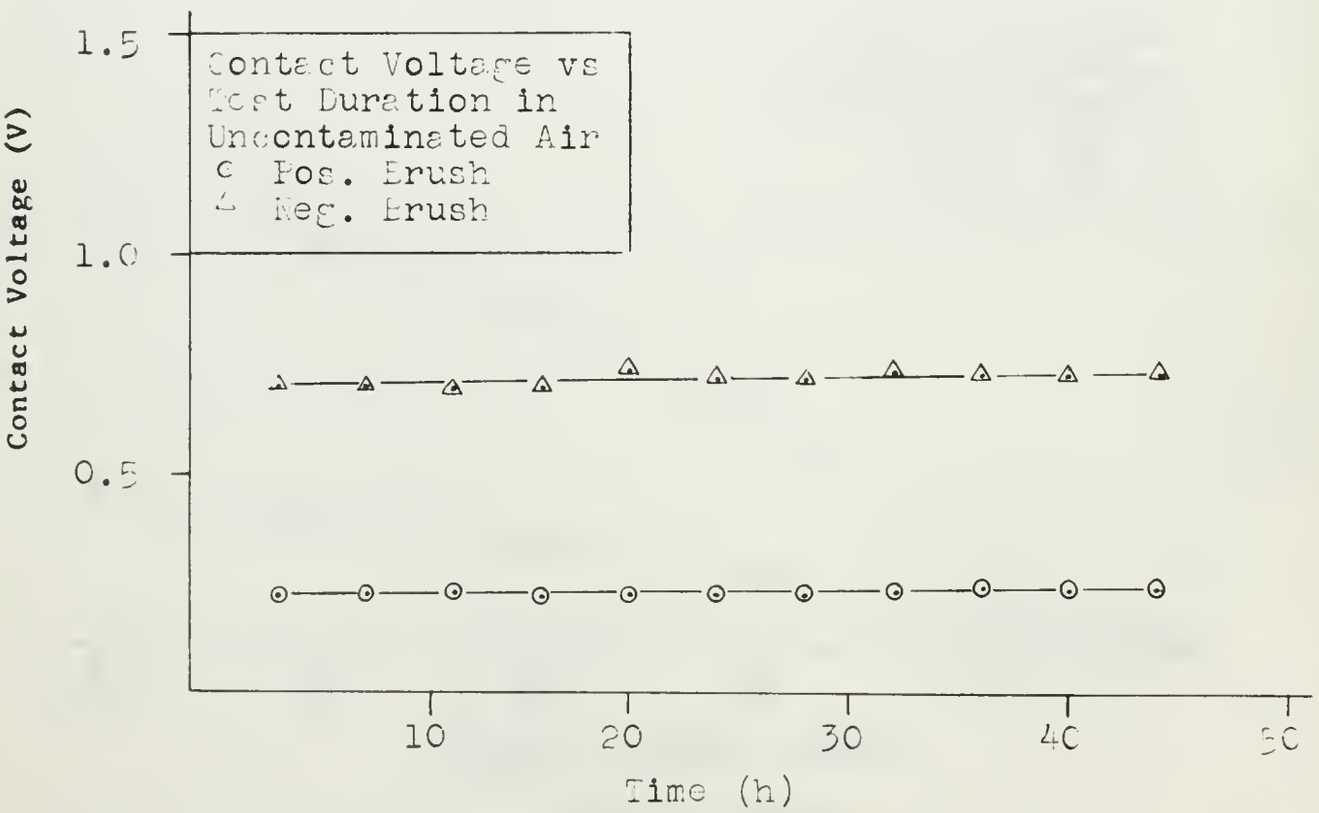

Figure 12L.

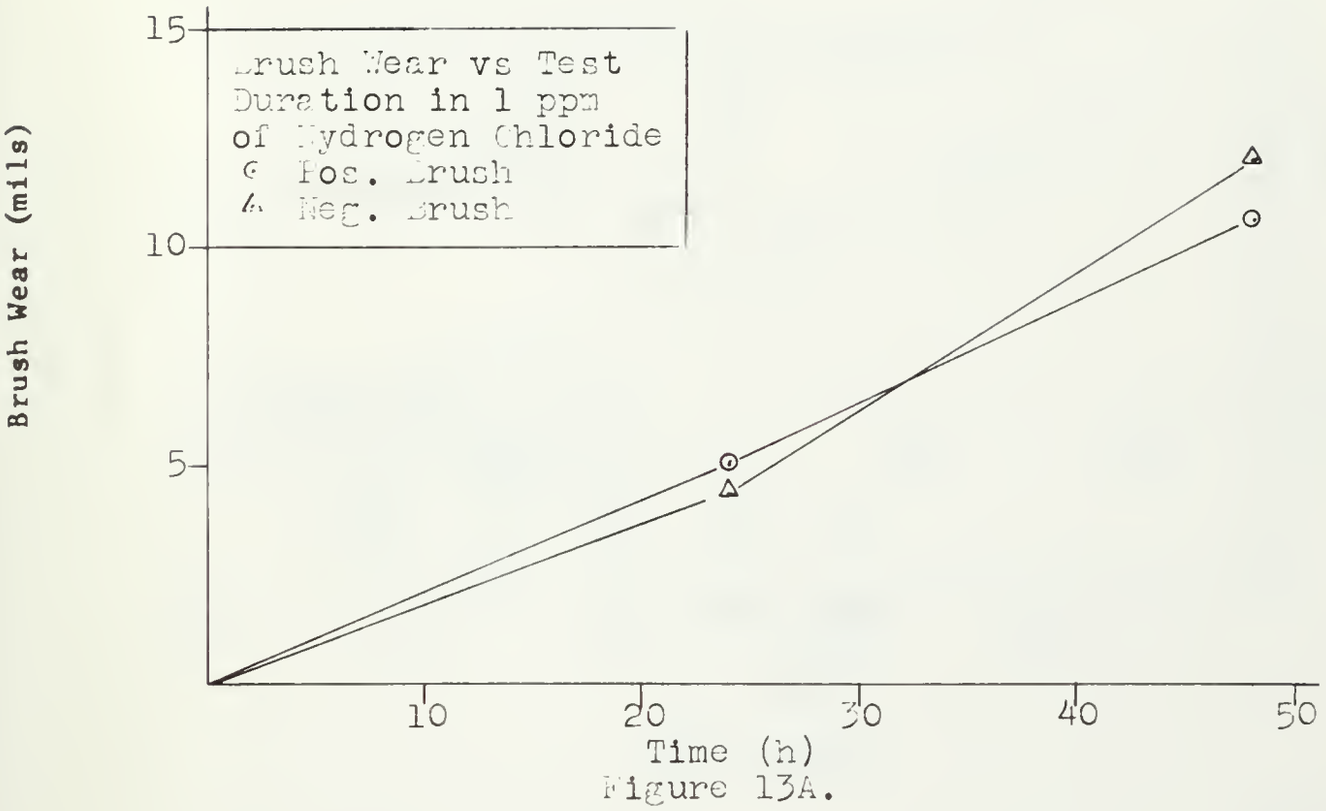

Figure 13A.

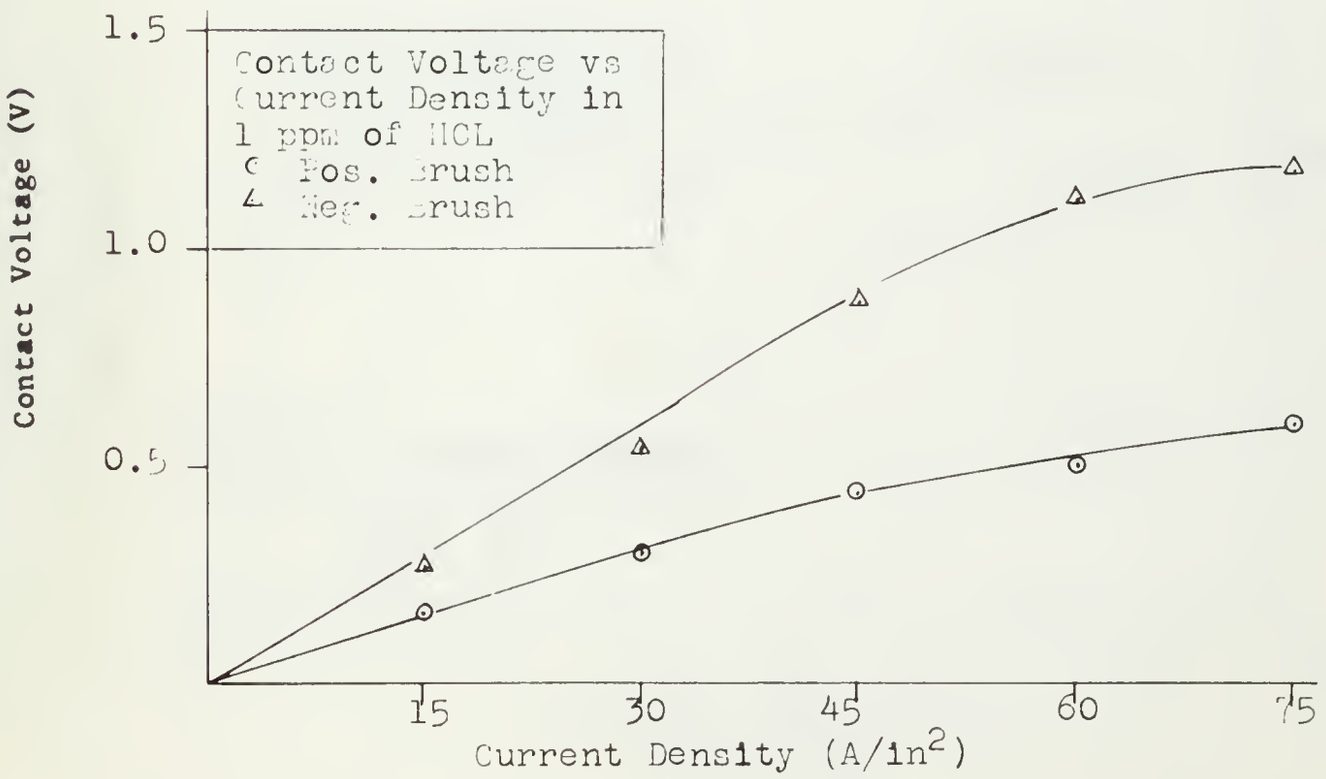

Figure 13B.

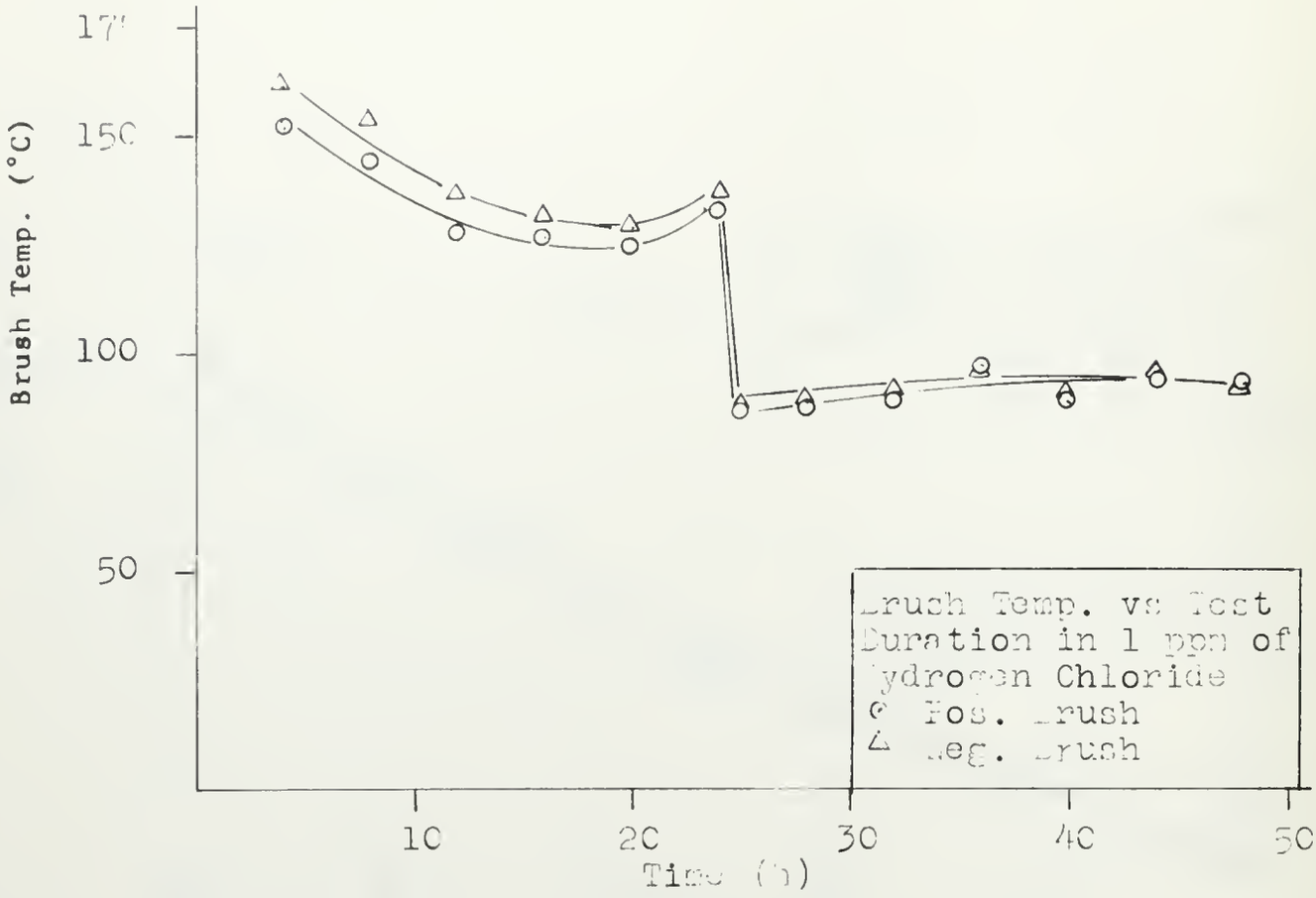

Figure 13C.

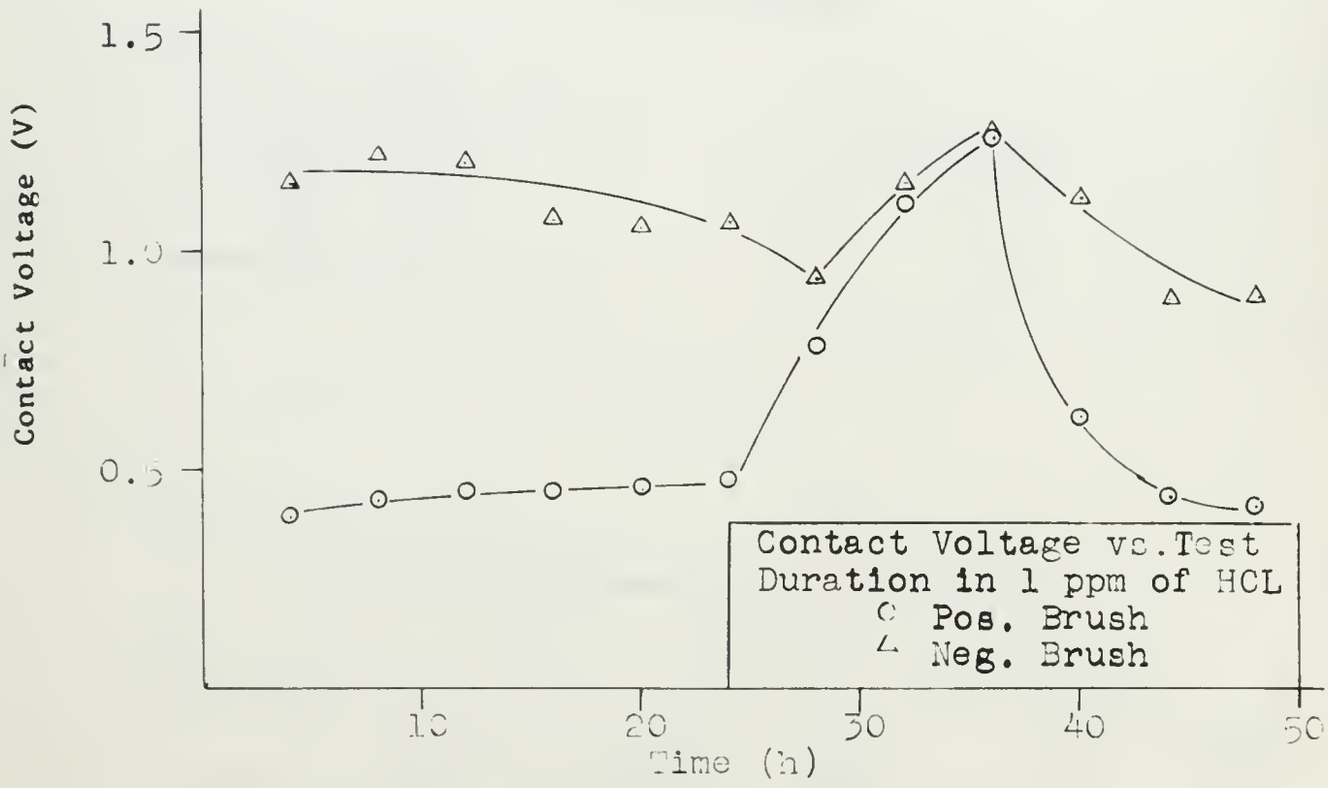

Figure 13D.

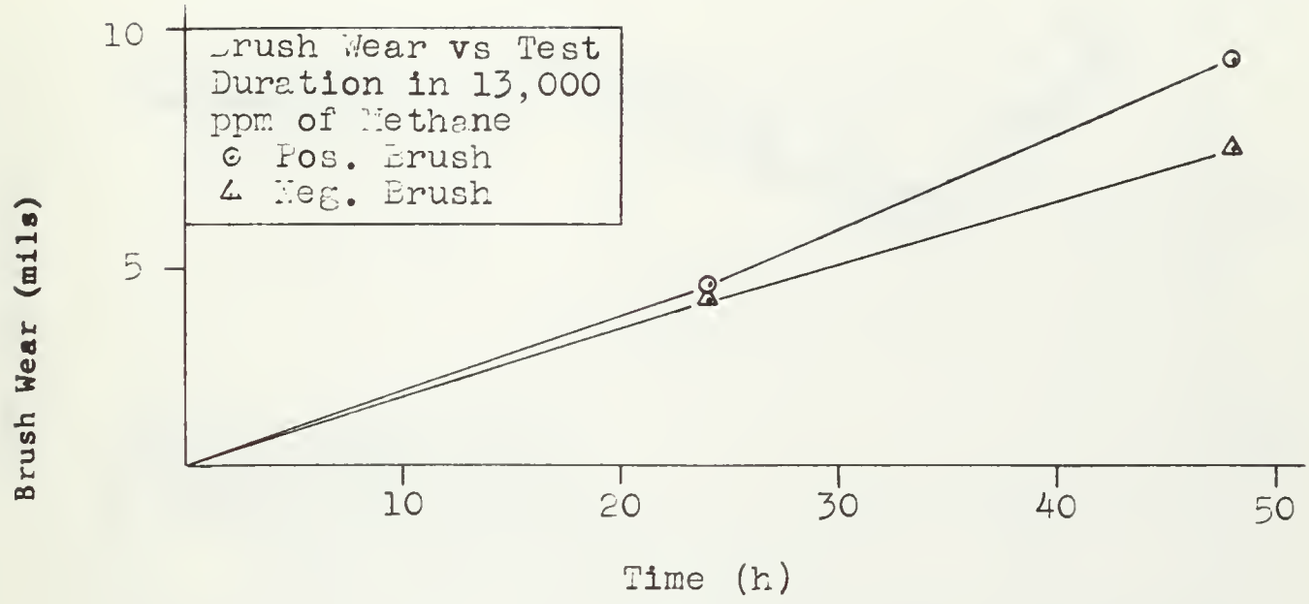

Figure 14A.

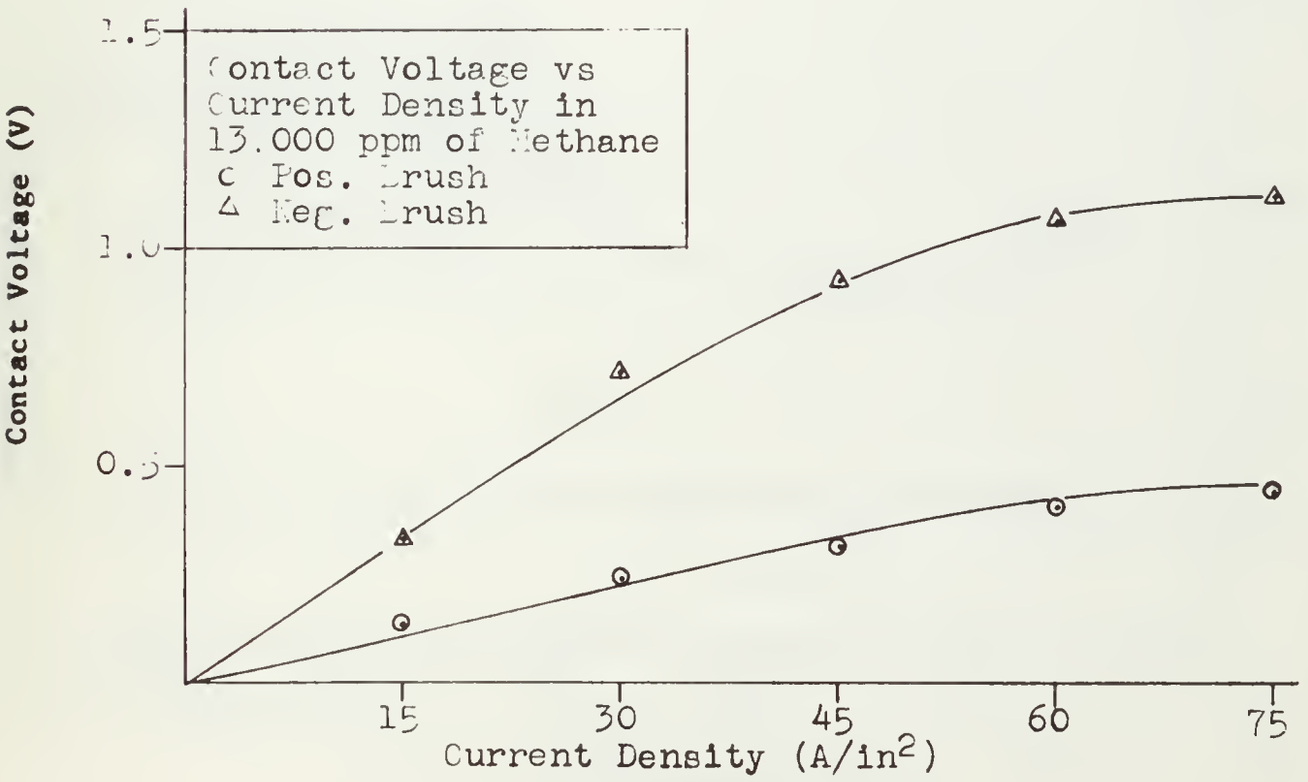

Figure 14B.

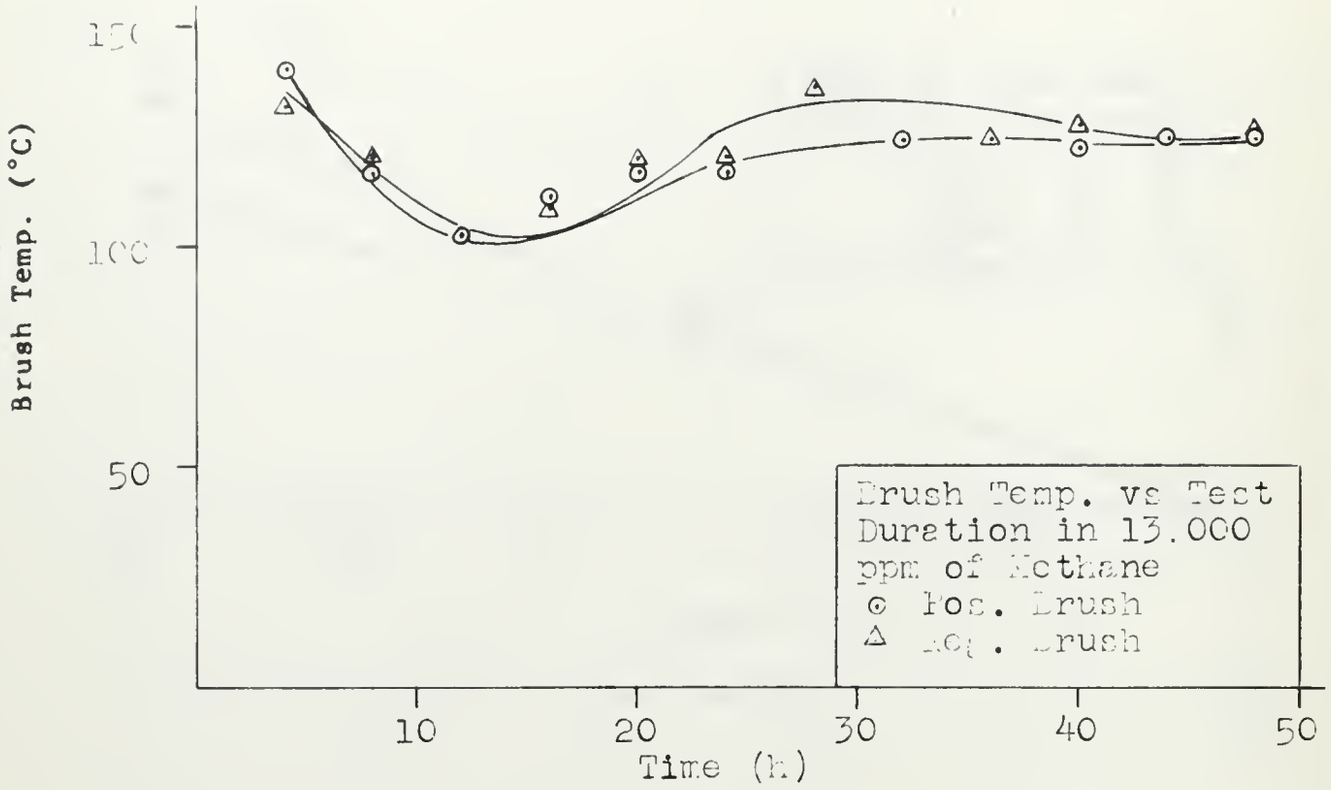

Figure 14C.

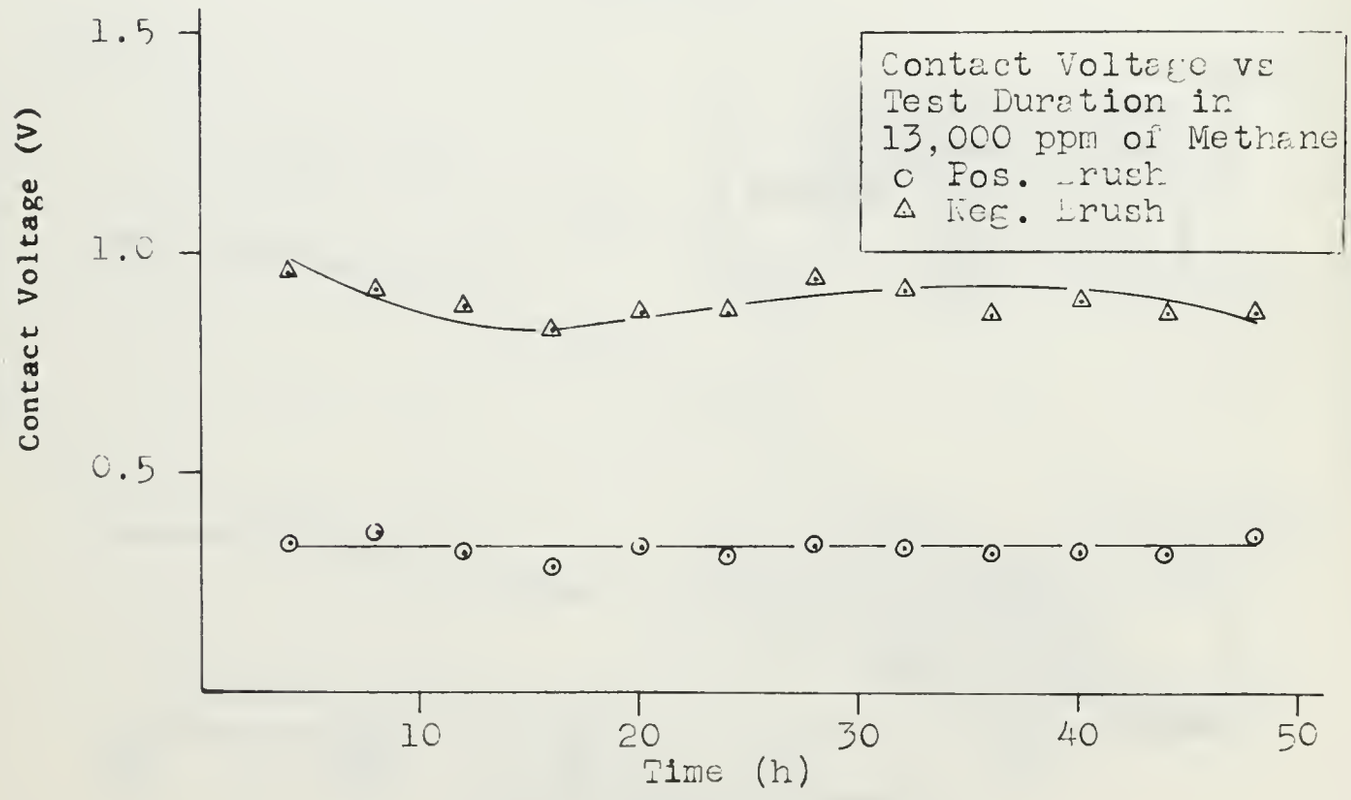

Figure 14D.

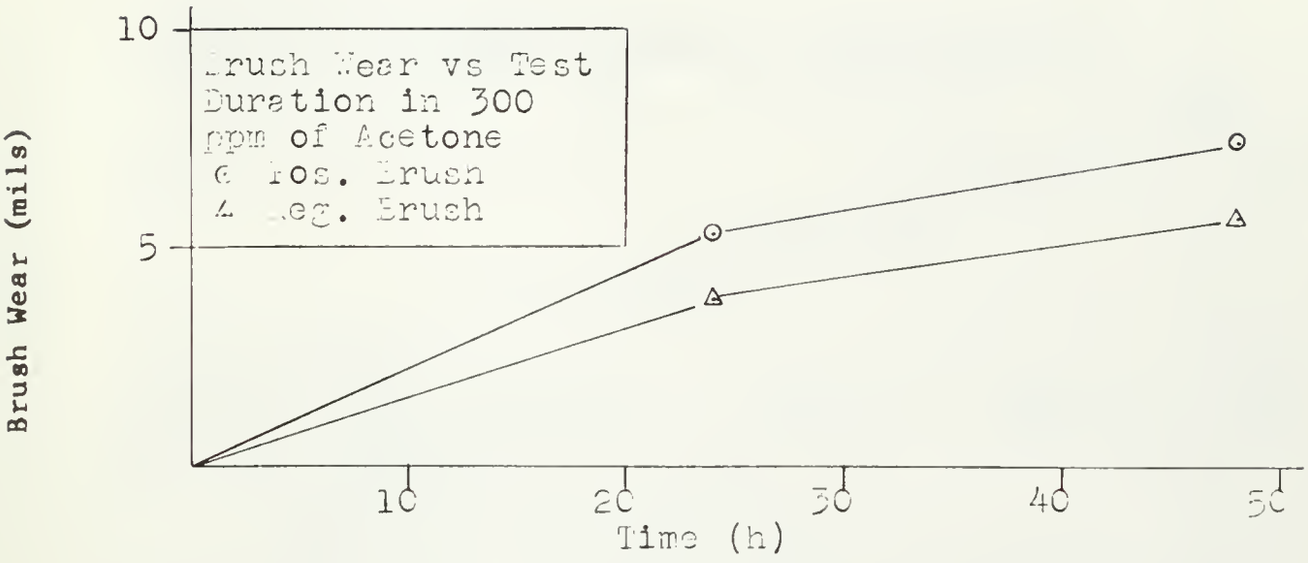

Figure 15A.

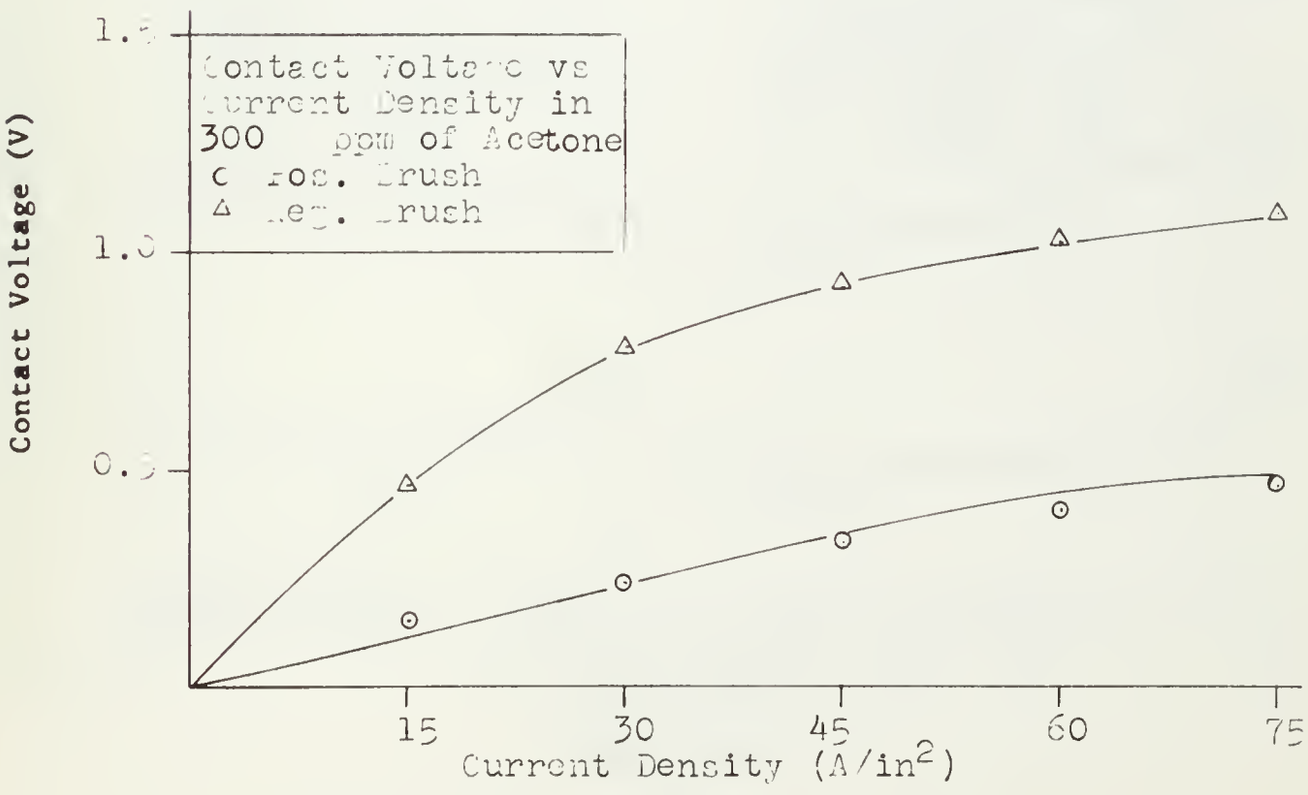

Figure 15B.

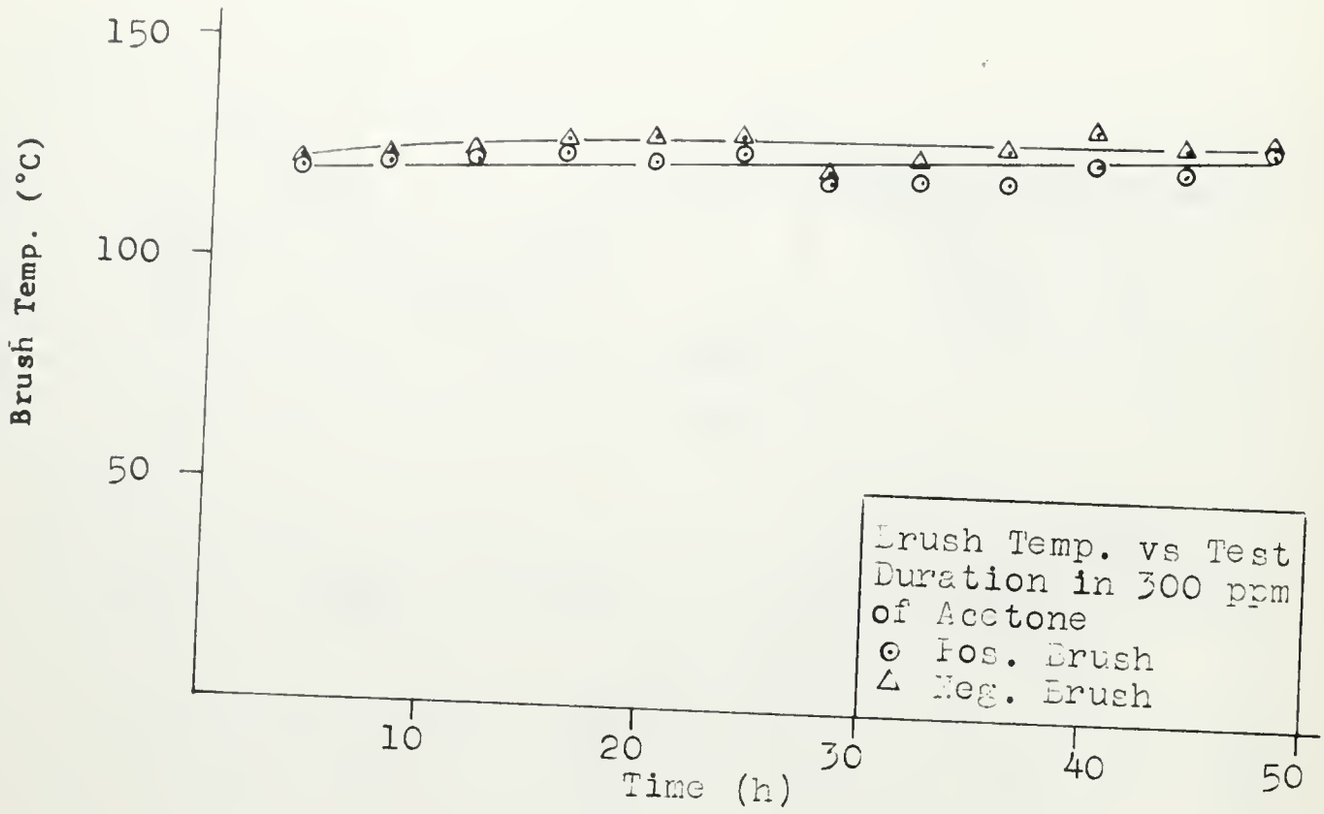

Figure 15C.

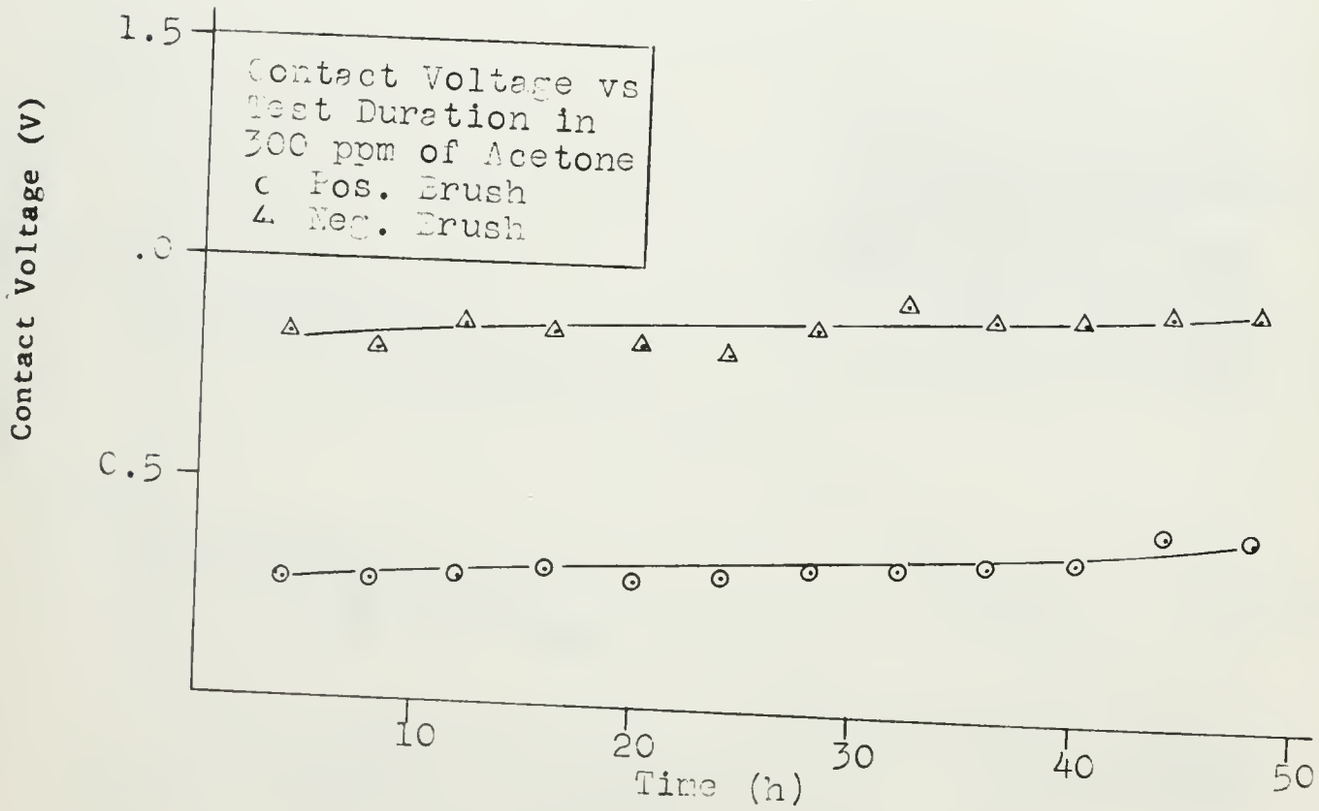

Figure 15D.

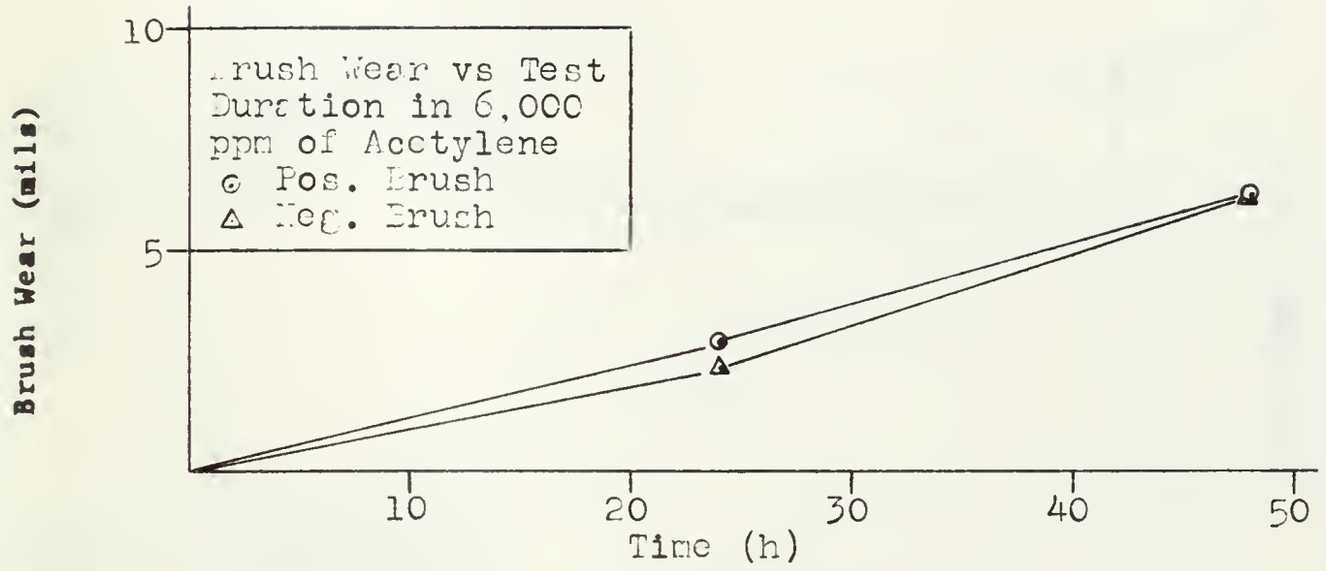

Figure 16A.

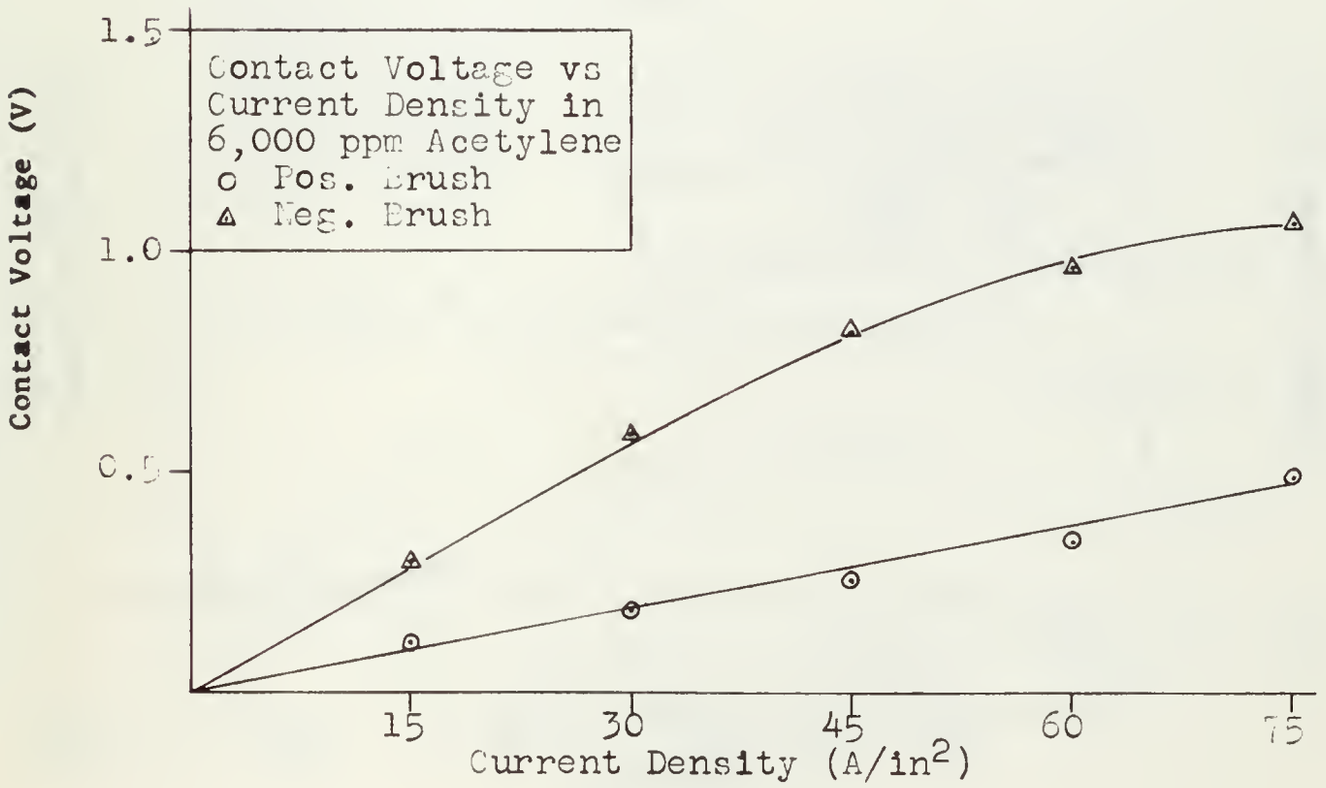

Figure 16B.

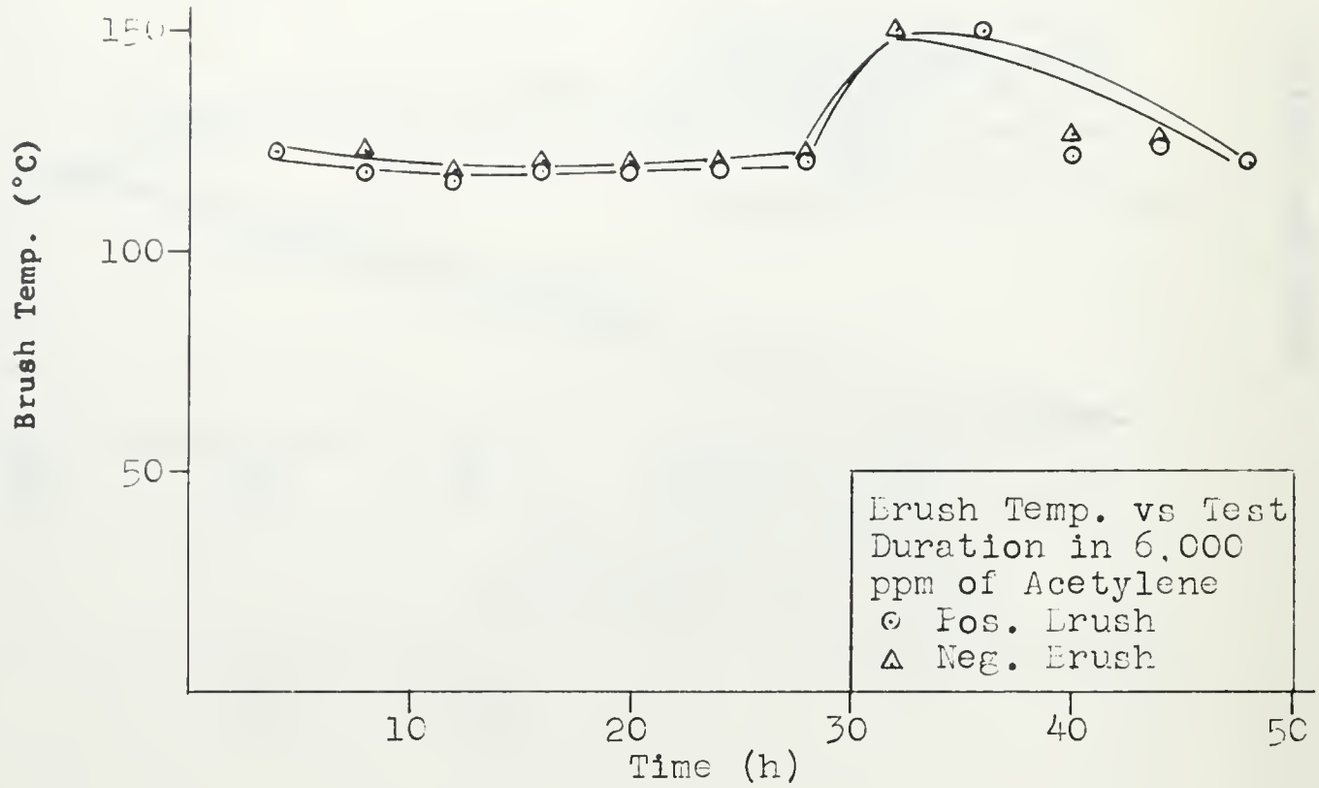

Figure 16C.

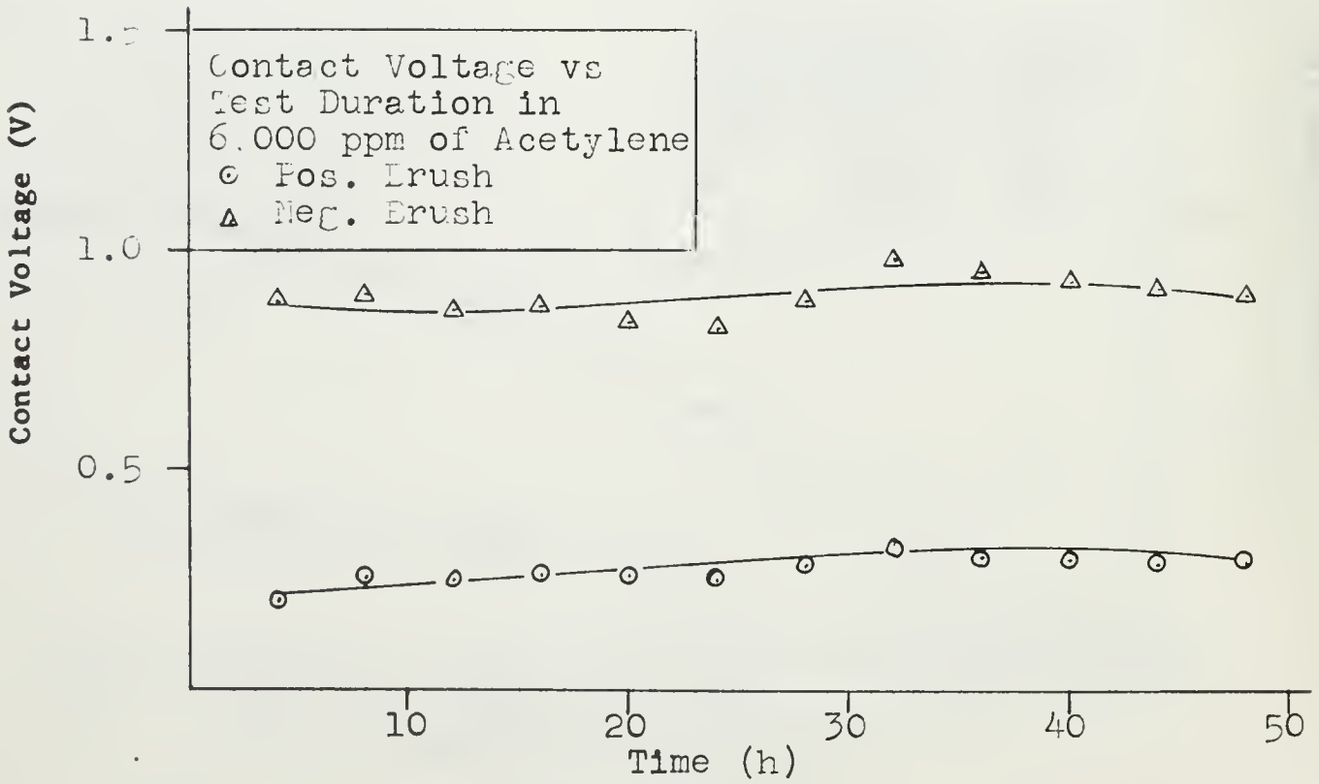

Figure 16D.

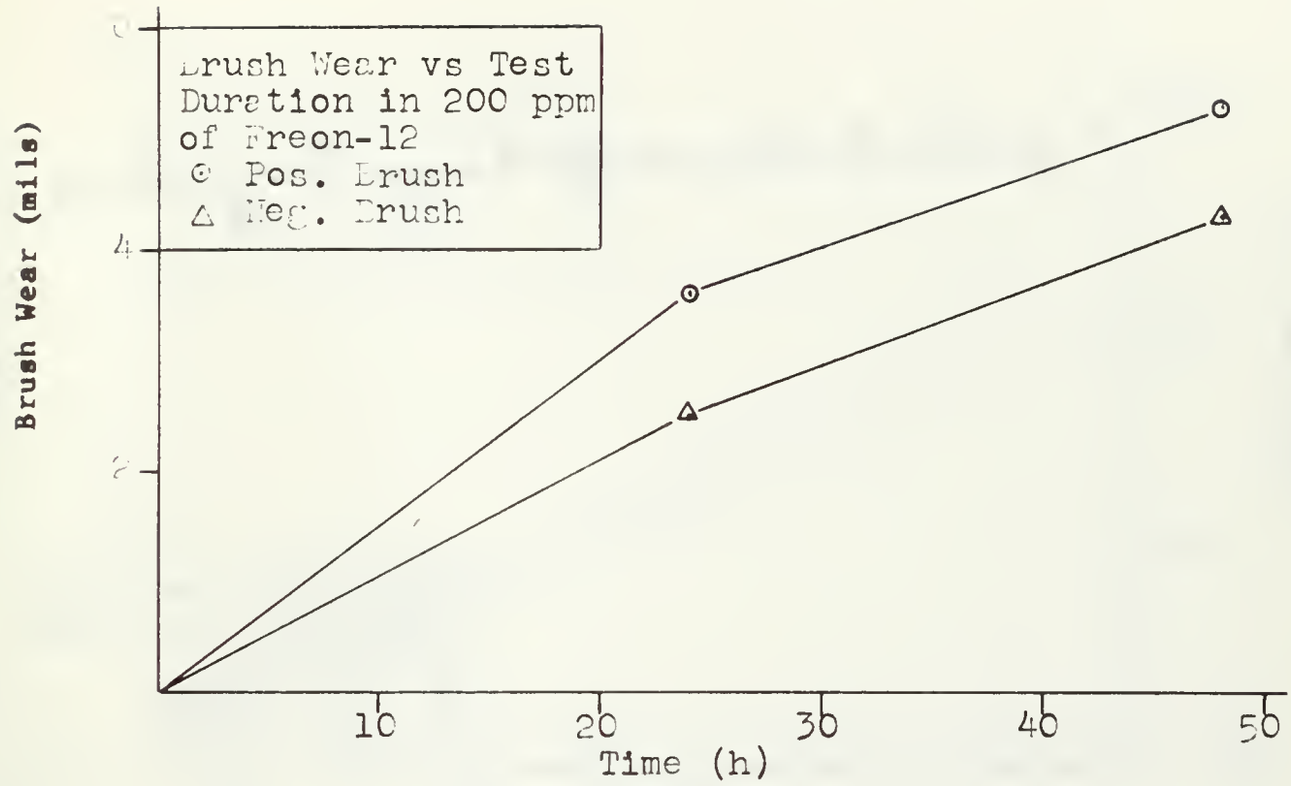

Figure 17A.

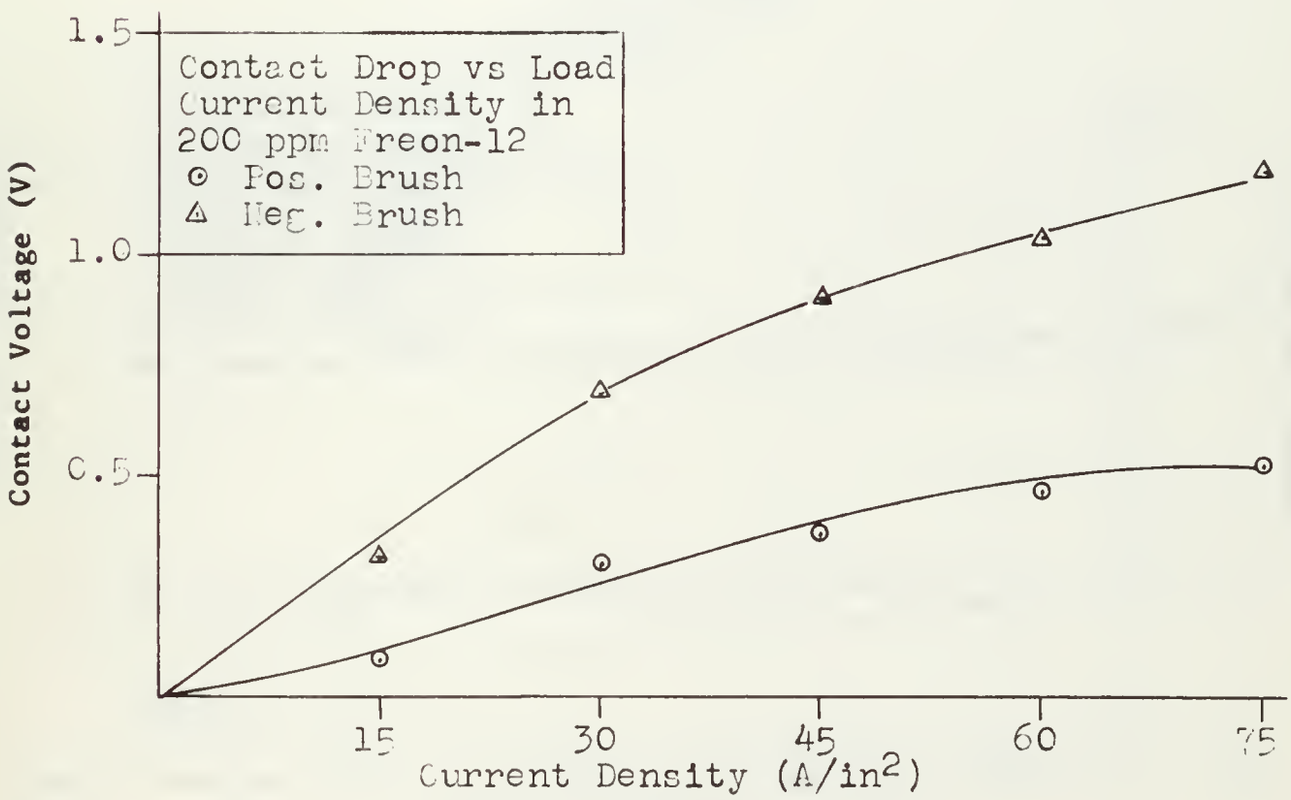

Figure 17B.

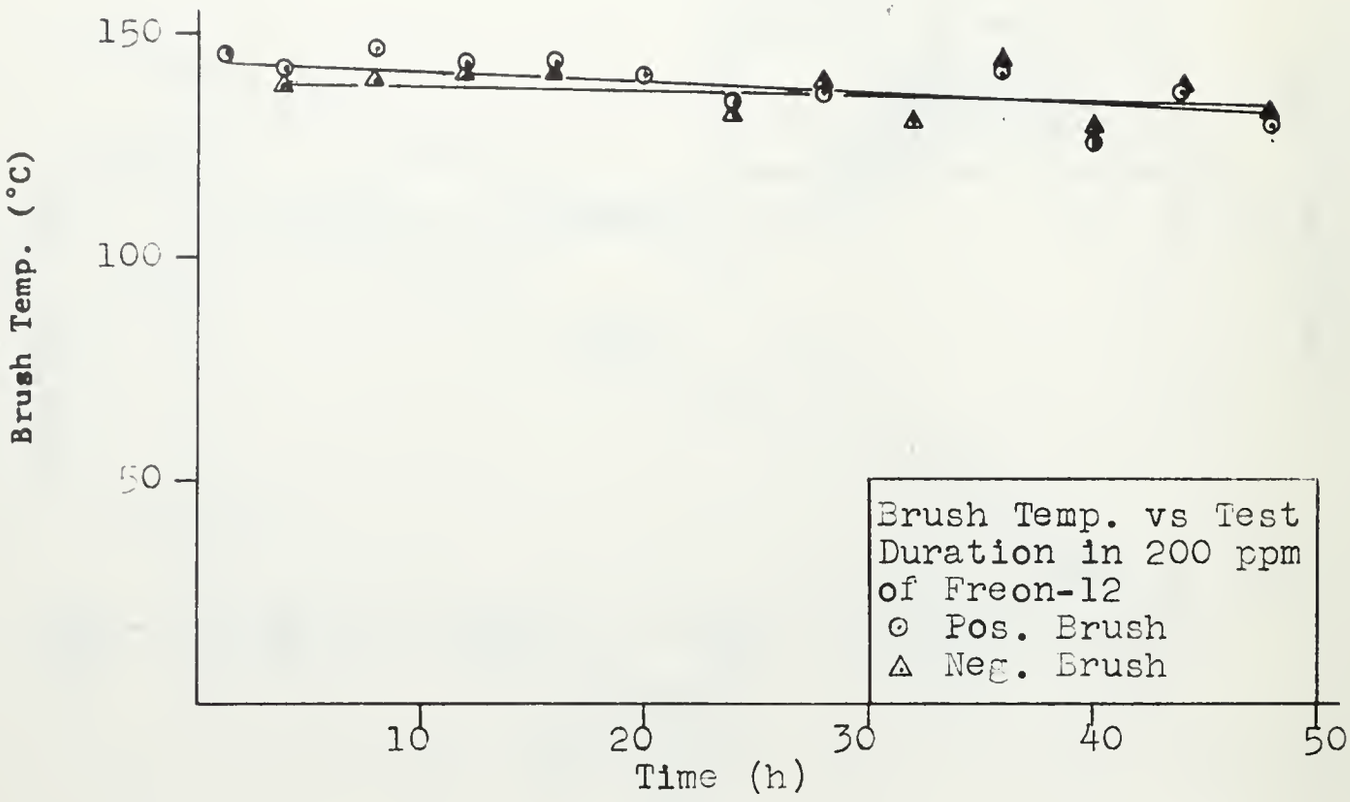

Figure 17C.

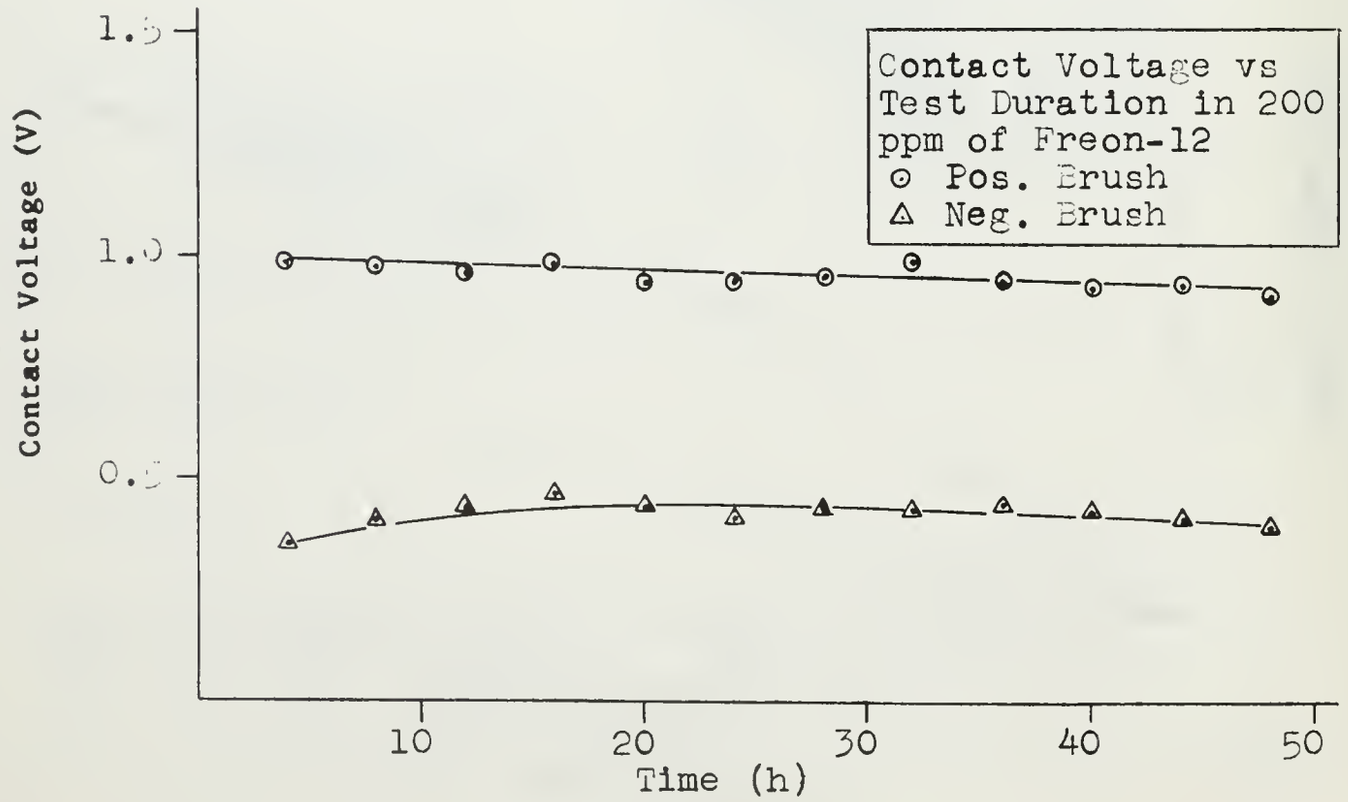

Figure 17D.

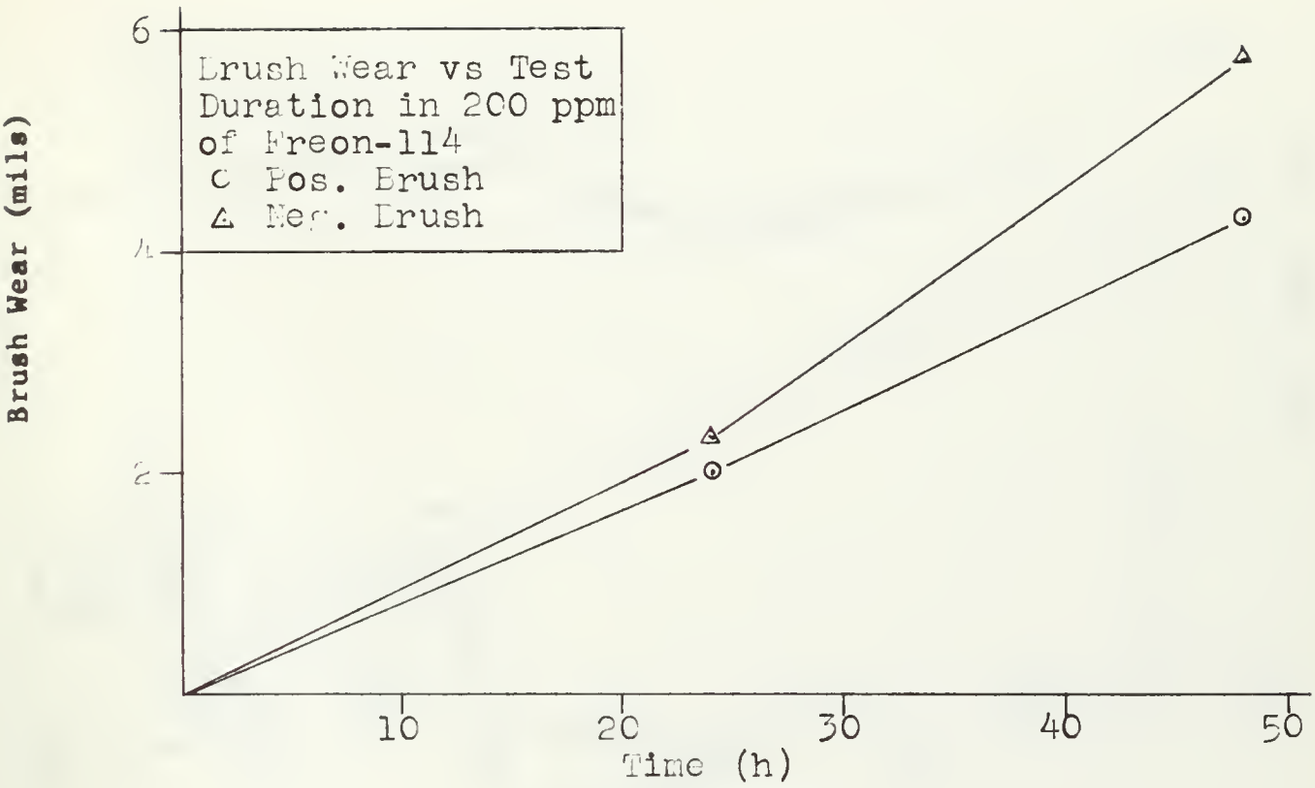

Figure 18A.

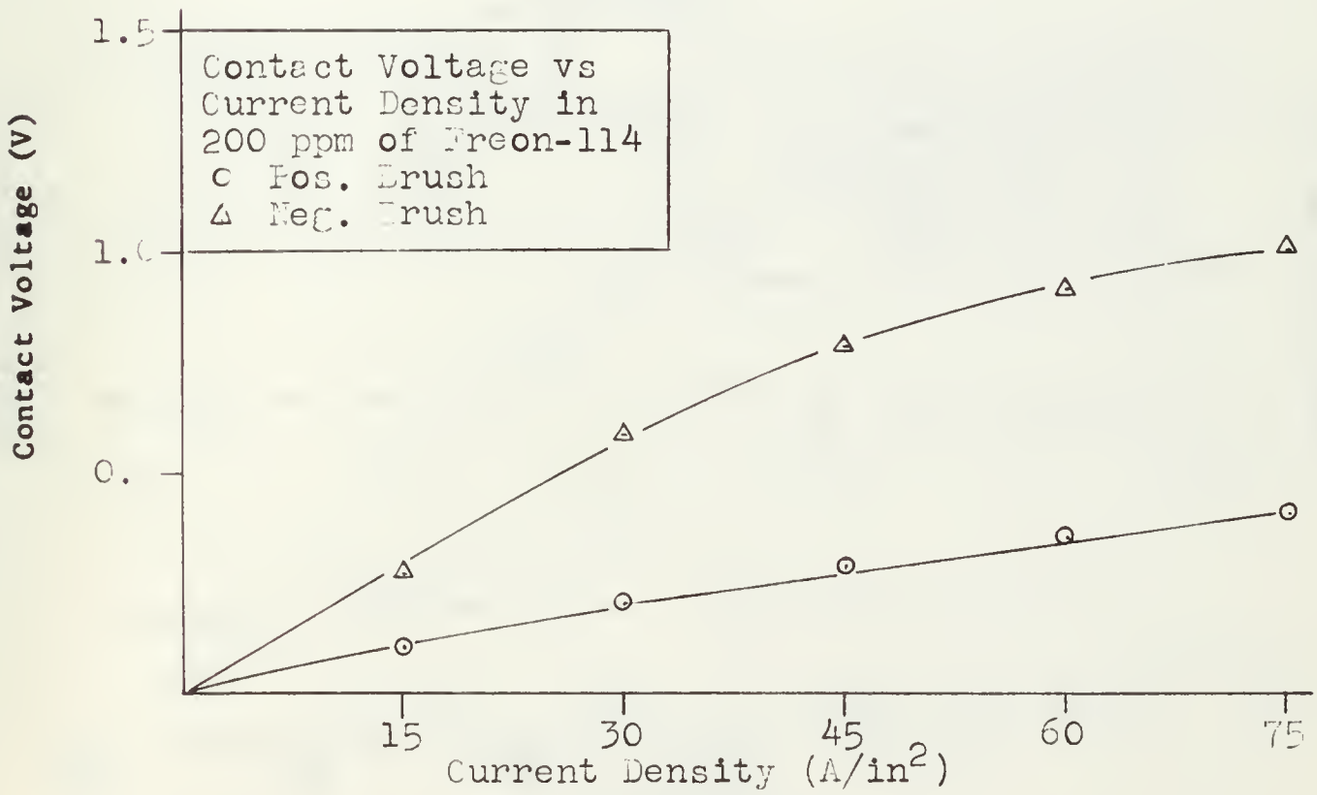

Figure 18B.

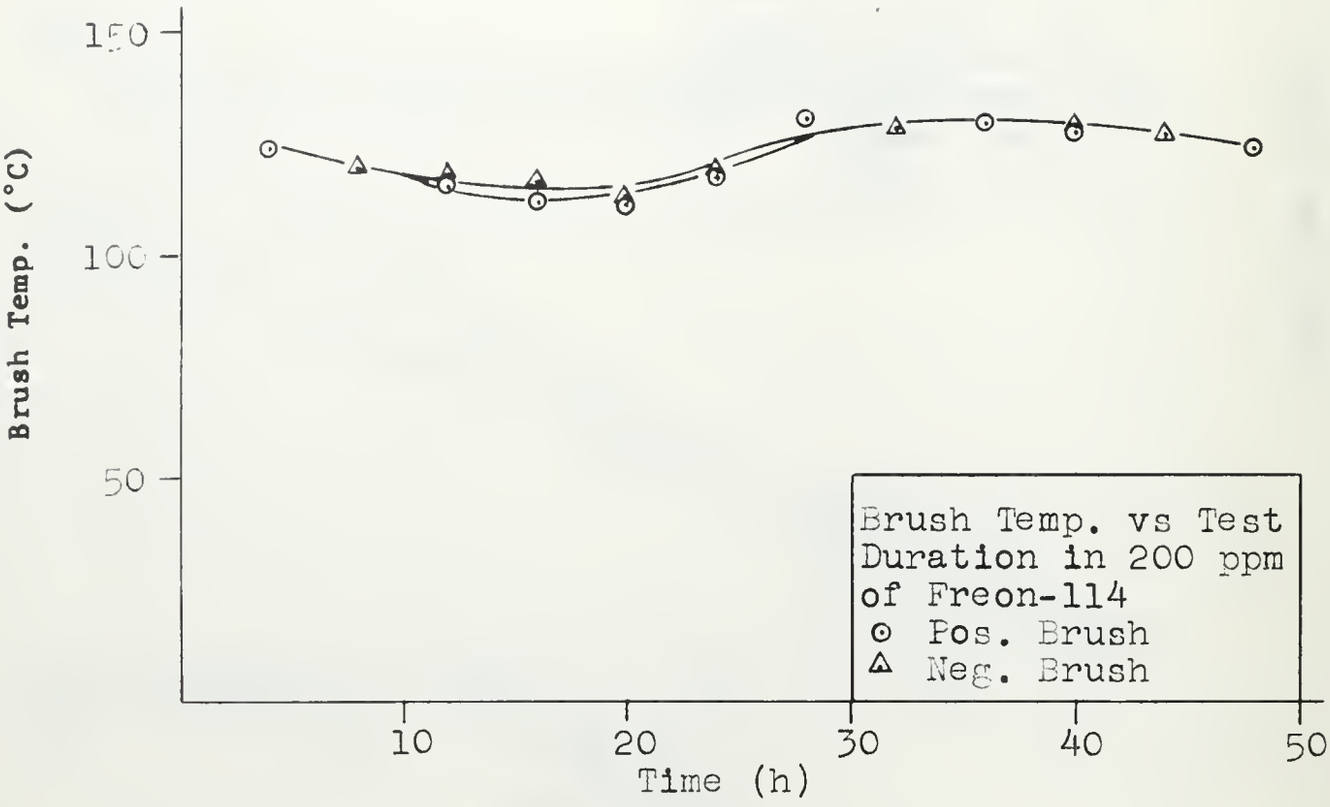

Figure 18C.

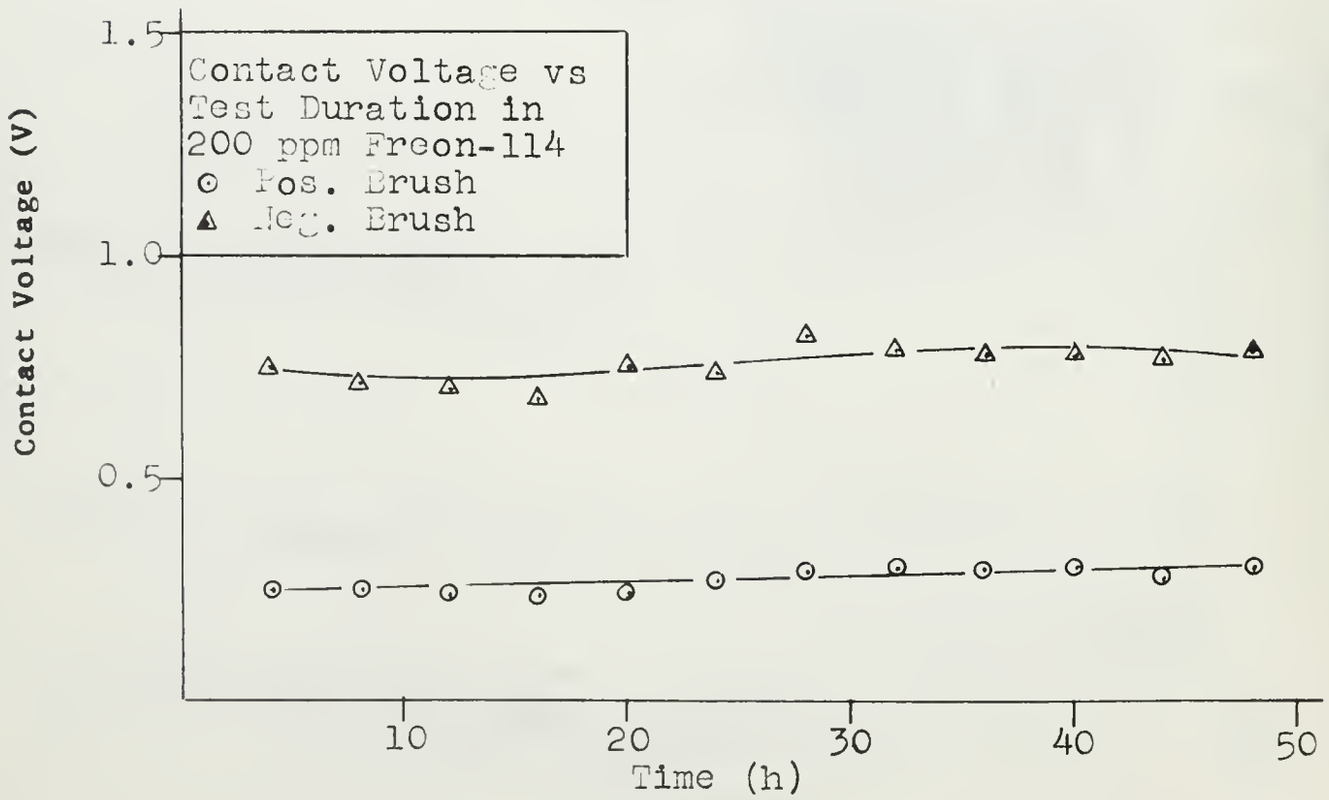

Figure 18D.

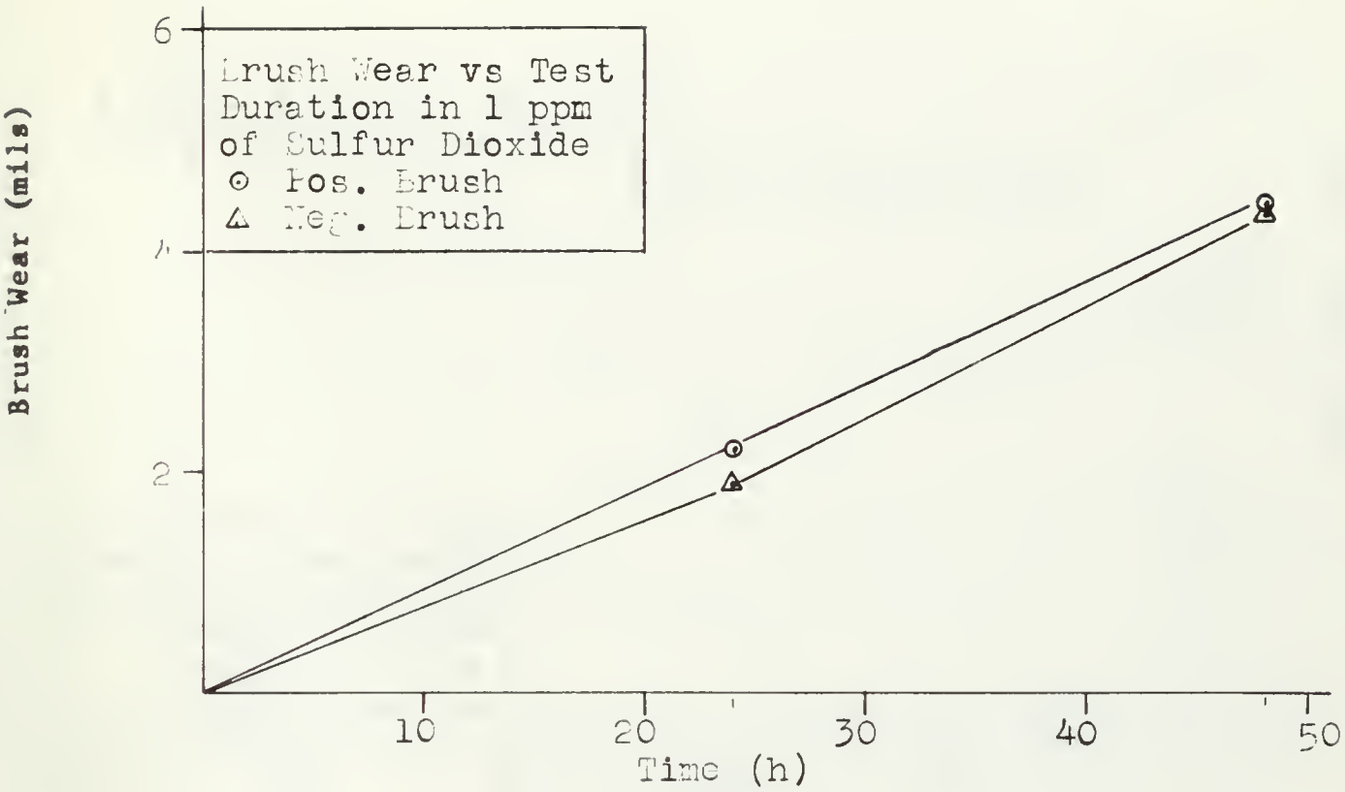

Figure 19A.

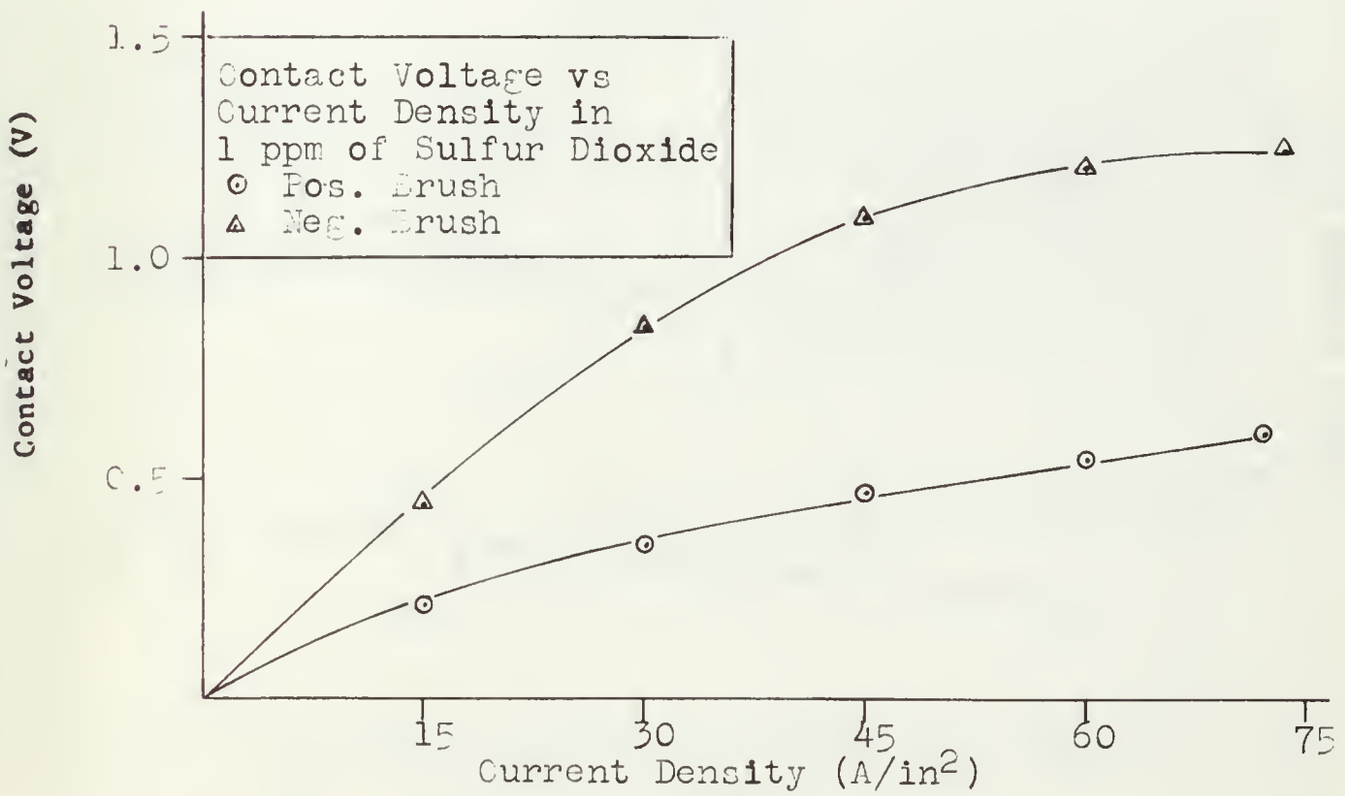

Figure 19B.

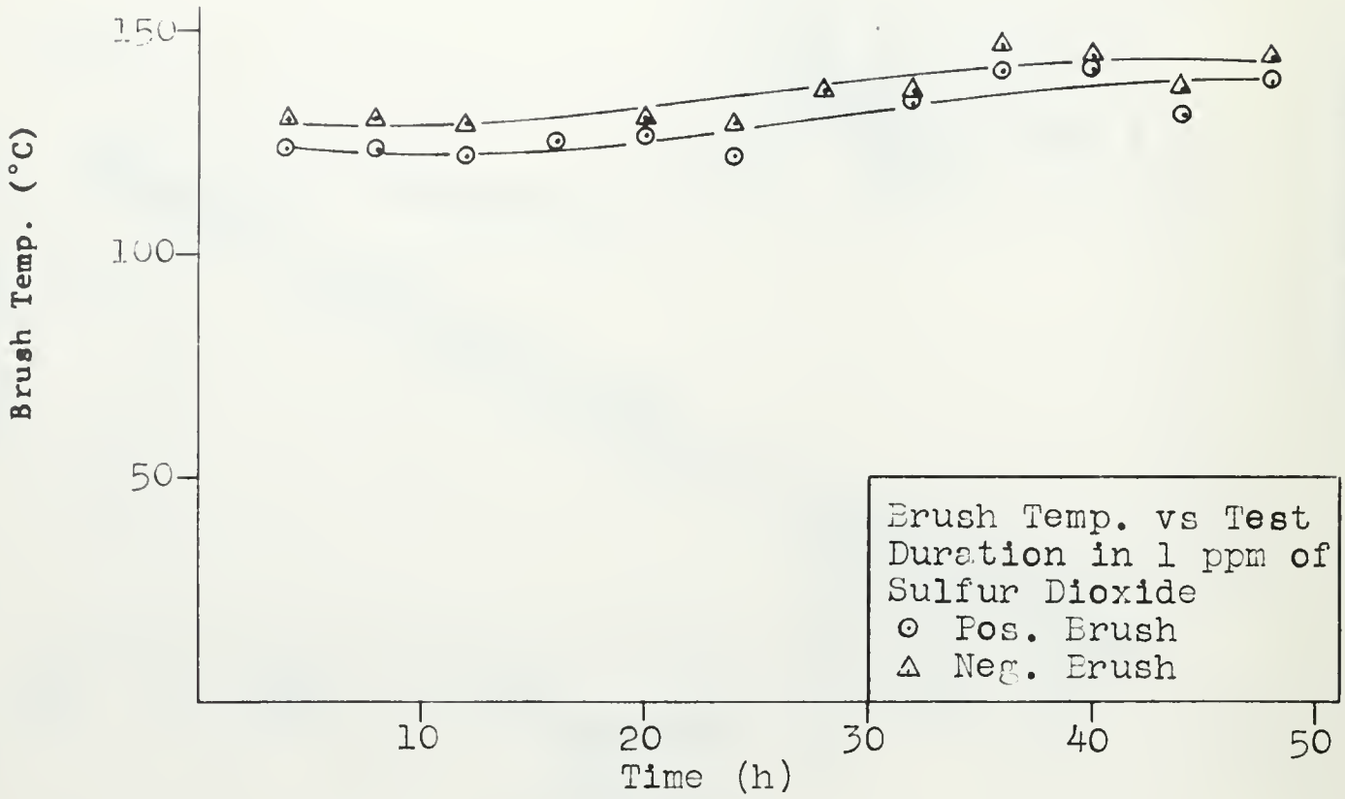

Figure 19C.

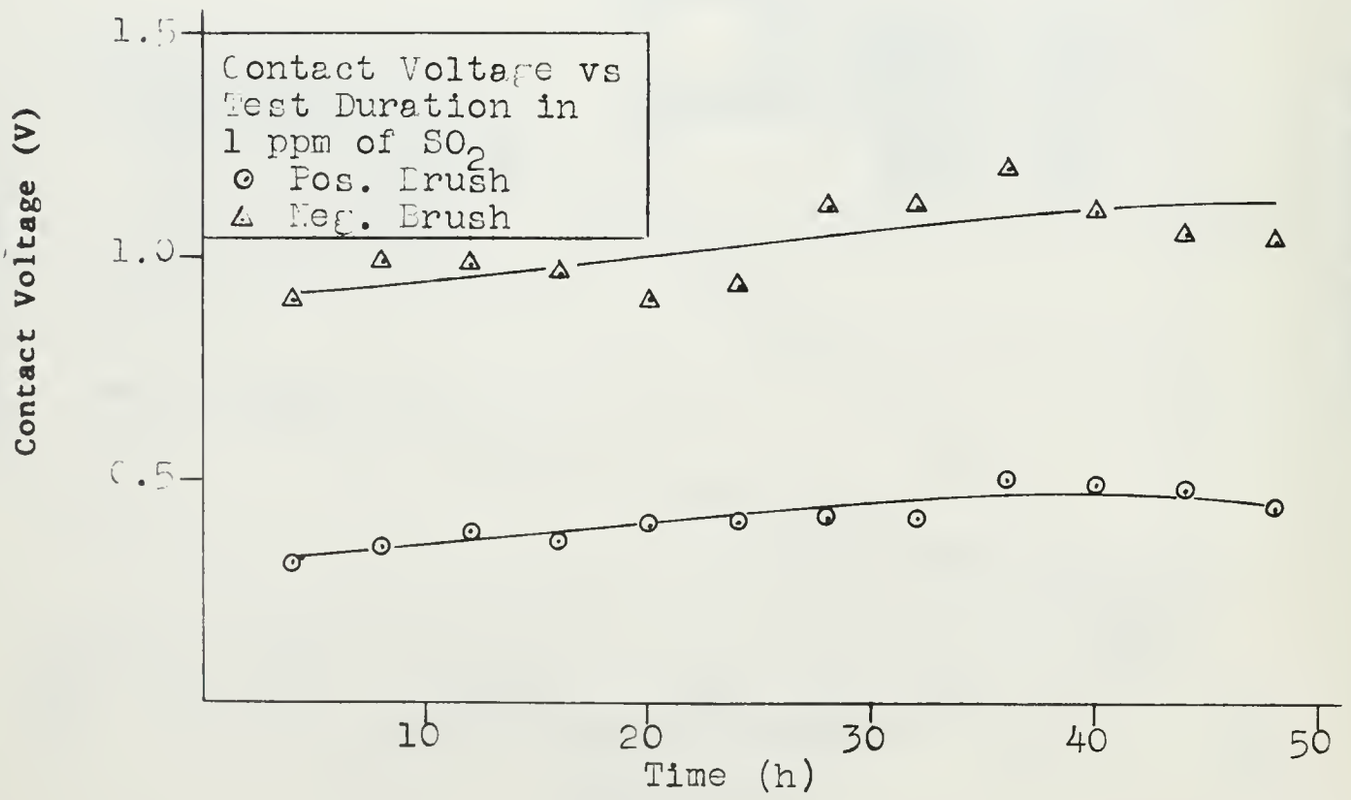

Figure 19D.

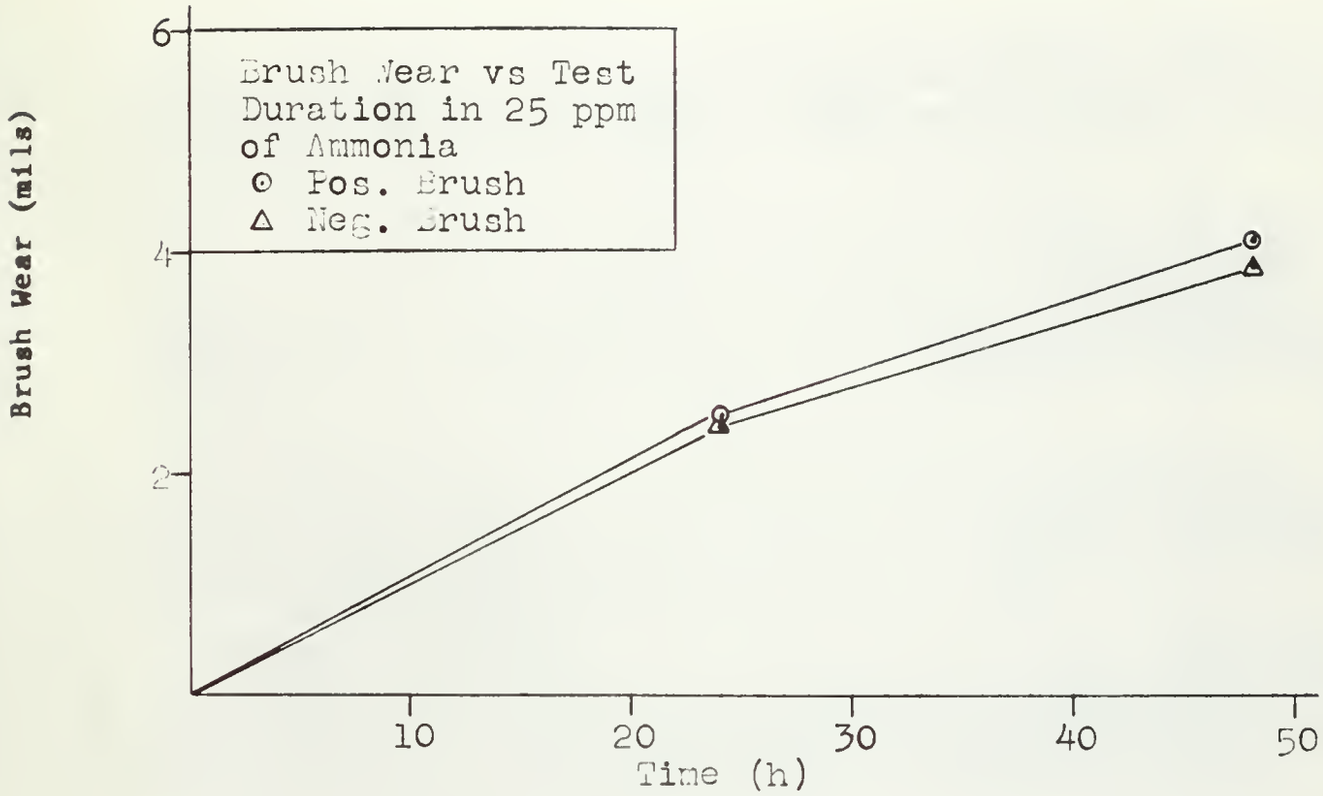

Figure 20A.

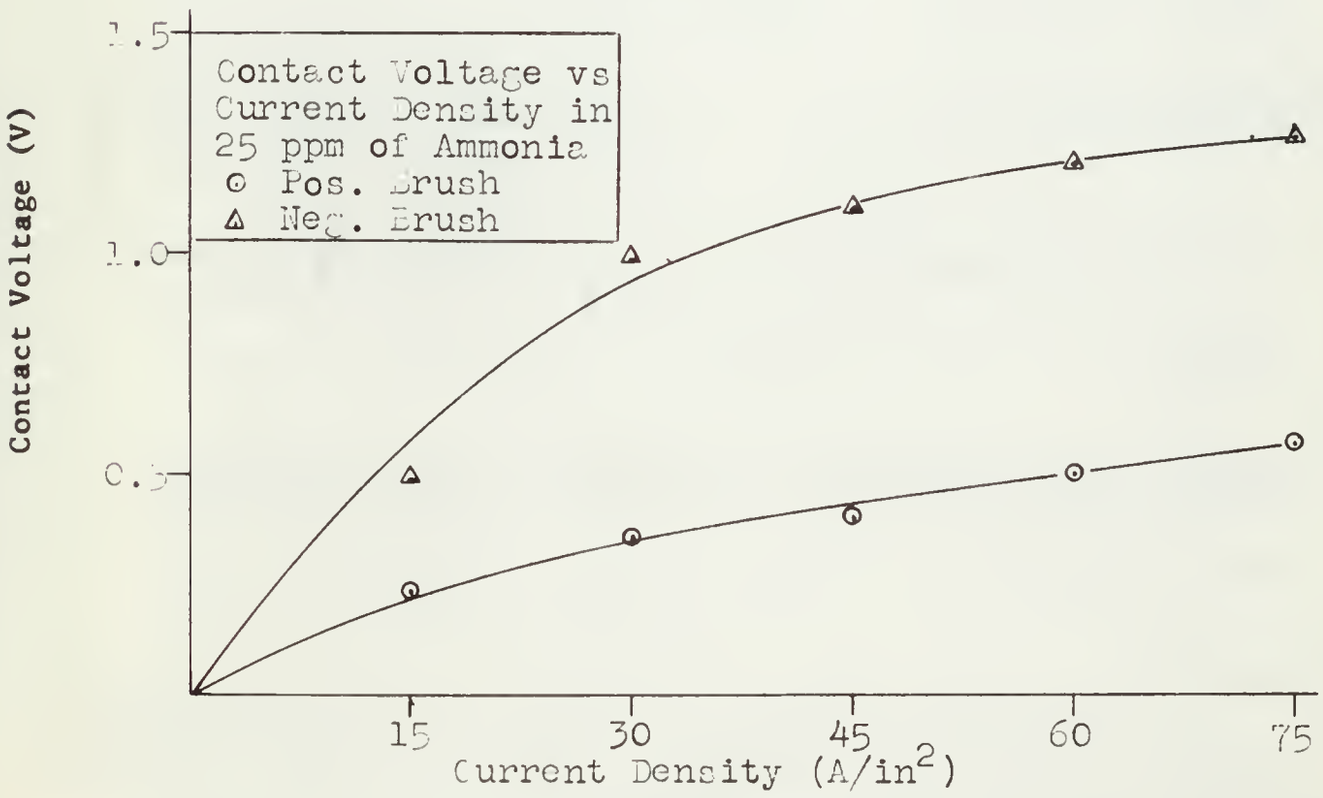

Figure 20B.

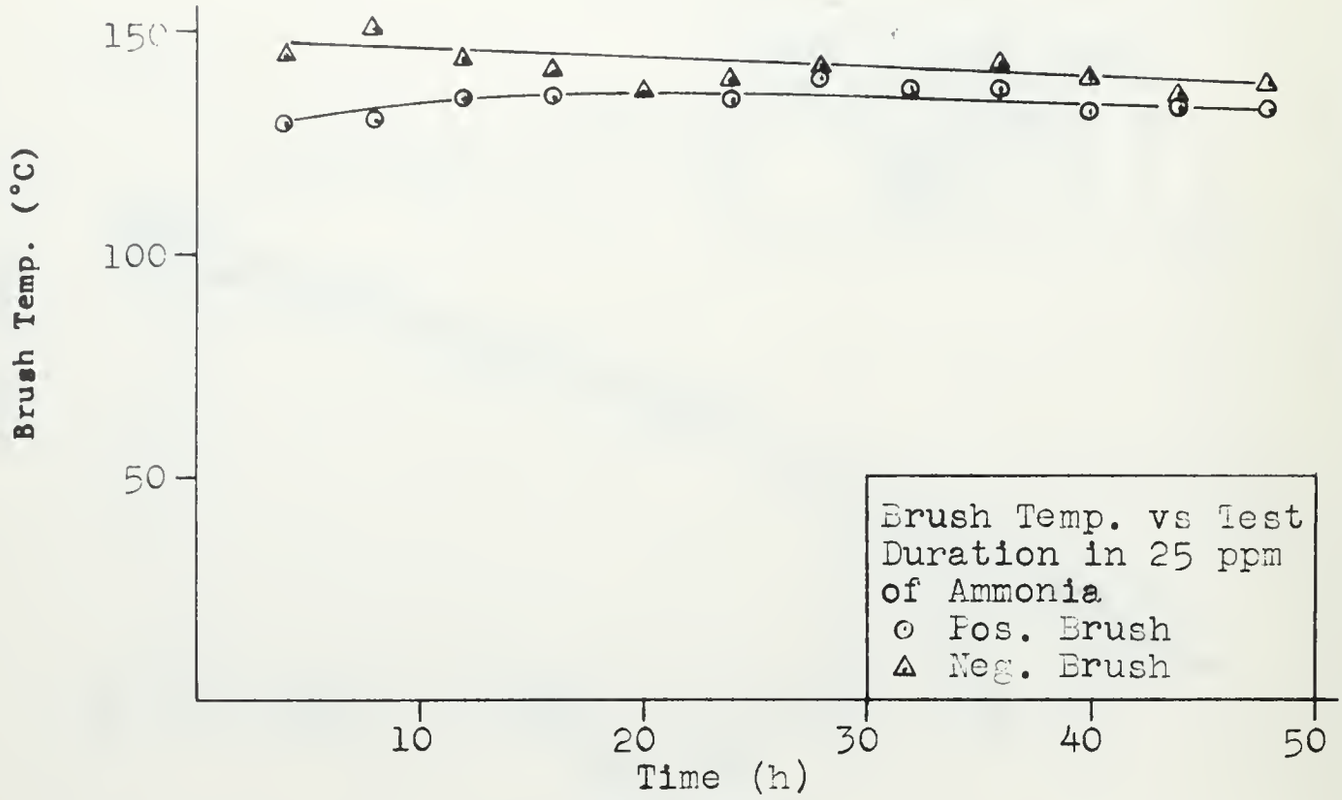

Figure 20C.

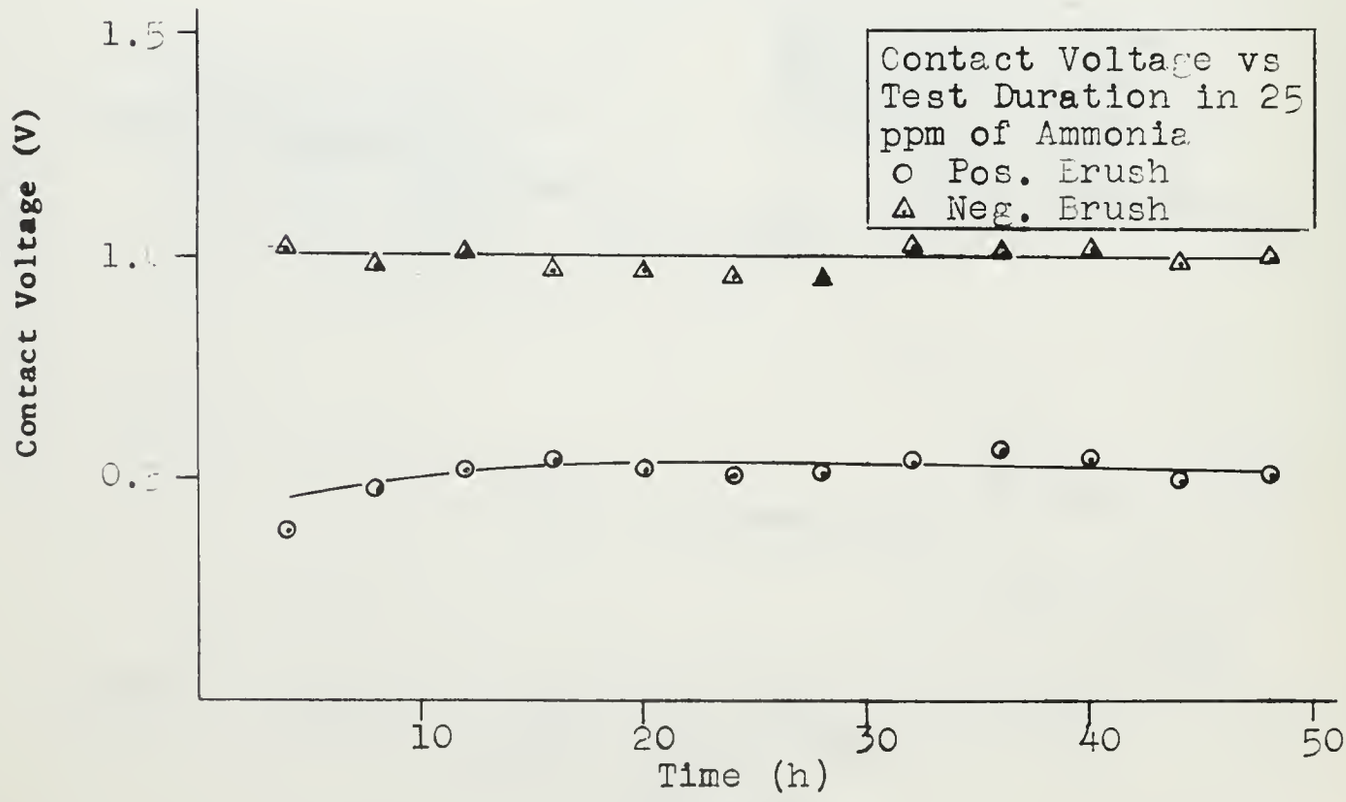

Figure 20D.

BIBLIOGRAPHY

1. Naval Ship Systems Command UNCLASSIFIED Letter NAVSHIP 9614 Serial 6660H - 3544 to Naval Ship Engineering Center, Philadelphia Division, et al., Subject: Allis Chalmers 400 Cycle Motor Generators on SSB(N) 640 Class Submarines, 27 October 1966.

2. Naval Ship Systems Command UNCLASSIFIED Letter NAVSHIP 9614 Serial 660H - 3845 to Commander, Submarine Force, U. S. Atlantic Fleet, et al., Subject: Unsatisfactory Performance of Commutators and Brushes on Allis Chalmers 64 KW and 30/10 KW Motor Generators and Safety Electric 64 KW Motor Generators on Submarines, 28 November 1966.

3. Naval Ship Engineering Center UNCLASSIFIED Letter NAVSEC 9614 Serial 6158C - 1404 to Naval Ship Engineering Center, Philadelphia Division, Subject: Operational Tests of 30/10 KW Motor Generator to Evaluate Slip Ring Performance, 29 April 1968.

4. Naval Ship Engineering Center, Philadelphia Division, UNCLASSIFIED Letter 9614 (FM-580) Serial 6732/OLR:213 to Naval Ship Engineering Center, Subject: Allis Chalmers 30/10 KW and 64 KW Motor Generator Tests to Evaluate Slip Ring Performance; Progress Report No. 3 (August), 2 August 1968.

5. Maintenance Support Office Report SR - 66 - 00083 - 03, Remap Report 8 - Selected Equipment History, January 1969.

6. Bibliography and Abstracts on Electrical Contacts, Circuit Breakers, and Arc Phenomena, 1951 to 1953 with annual supplements through 1963, American Society of Testing Materials.

7. Holm, R., Electric Contacts Theory and Application, 4th ed., Springer-Verlag, 1967.

8. Holm, R., Electric Contacts Handbook, 3rd ed., p. 9, Springer-Verlag, 1958.

9. Shobert, E. I., Carbon Brushes: The Physics and Chemistry of Sliding Contacts, p. 5-6, Chemical Publishing Company, 1965.

10. Holm, H., Electric Contacts: Theory and Application, 4th ed., p. 135-143, Springer-Verlag, 1967.

11. Uhlig, H. H., Corrosion and Corrosion Control, p. 159, Wiley, 1965.

12. Holm, E., "Dependence of the Conduction Mechanism on Polarity in Stationary and Sliding Contacts When High-Resesitivity Film is Present in the Contact", IEEE Trans. on Power Apparatus and Systems, v. 84, no. 5, p. 404-411, May 1965.

13. Holm, H., Abstracts of Papers on Electrical Contacts, paper presented at Engineering Seminar on Electrical Contacts, Pennsylvania State University, 9-14 June 1957.

14. Holm, R., Electric Contacts: Theory and Application, p. 135-152, Springer-Verlag, 1967.

15. Holm, E., "Contribution to the Theory of the Contact between a Carbon Brush and a Copper Collector Ring", Journal of Applied Physics, v. 28, no. 10, 1171-1176, October 1967.

16. Holm, R., "Contribution to the Theory of the Brush-Collector Contact", AIEE Trans., pt. III, v. 78, p. 431-439, August 1959.

17. Holm, R., "Temperature Development in a Heated Contact with Application to Sliding Contacts", Journal of Applied Mechanics, v. 19, p. 369-374, September 1952.

18. Holm, R., "Electric Contacts: Theory and Application", p. 92-102, Springer-Verlag, 1967.

19. Shobert, E., "Calculation of Temperature Transients in Carbon Brushes", IEEE Trans. on Power Apparatus and Systems, v. 87, no. 10, October 1968.

20. Shobert, E. I., Carbon Brushes: The Physics and Chemistry of Sliding Contacts, p. 138-152, Chemical Publishing Company, 1965.

21. Holm, R., Electric Contacts: Theory and Application, p. 250-260, Springer-Verlag, 1967.

22. Ubbelohde, A. R., and Lewis, F. A., Graphite and its Crystal Compounds, p. 20-25, Clarendon Press, 1960.

23. Bryant, P. J., Gutshall, P. L., and Taylor, L. H., "A Study of Mechanism of Graphite Friction and Wear", Wear, v. 7, p. 118, April 1964.

24. Van Brunt, C., and Savage, R. H., "Carbon-Brush Contact Films: Part 1", General Electric Review, v. 47, p. 16-19, July, 1944.

25. Hessler, V. P., "Electrical Brush Wear", Electrical Engineering, v. 54, p. 1050-54, October 1935.

26. Lancaster, J. K., "The Influence of the Conditions of Sliding on the Wear of Electrographitic Brushes", British Journal of Applied Physics, v. 13, no. 9, p. 468-477, September, 1962.

27. Baker, R. M., "Effect of Mercury Vapor on Sliding Contacts", Electric Journal, v. 29, p. 64-65, February 1932.

28. Baker, R. M., "Sliding Brush - Electrical Characteristics", AIEE Trans. v. 55, p. 94-100, January 1963.

29. Braken, E. F., "Humidity Control Prevents A. C. Brush Disintregration", Electric World, p. 410-411, 23 September 1933.

30. Dobson, J. V., "The Effect of Humidity on Brush Operation", Electric Journal, p. 527-28, December 1935.

31. Ramadanoff, D., and Glass, S. W., "High Altitude Brush Problems", AIEE Trans., v. 63, p. 825-30, November 1944.

32. Elsey, H. M., "The Treatment of High Altitude Brushes by the Application of Metallic Halides", AIEE Trans.,v. 64, p. 576-79, August 1945.

33. Savage, R. H., "Carbon-Brush Contact Films", General Electric Review, v. 48, 13-20, October 1945.

34. Horrel, R. F., Slip-Ring and Brush Applications Wound-Rotor Induction Machines, fig. 6, Helwig Carbon Products, 1965.

35. Paradee, R. P., "Moisture Dependence of Silver-Graphite Brushes in Air Nitrogen, Helium, and Carbon Dioxide", IEEE Trans.on Power Apparatus and Systems, v. 86, no. 5, p. 616-25, May 1967.

36. Savage, R. H., "Physically and Chemically Absorbed Films in the Lubrication of Graphite Sliding Contacts", Annuals of N. Y. Academy of Science, v. 53, p. 862-69, 1951.

37. Baker, R. M. and Hewitt, G. W., "Brush Wear in Hydrogen and in Air", Electric Journal, v. 33, no. 6, p. 287-89, June 1936.

38. Baker, R. M., and Hewitt, G. W., "Contact Drop and Wear of Sliding Contacts", Electrical Engineering, v. 56, p. 123-128, January 1937.

39. Lynn. C. and Elsey, H. M., "Effects of Commutor Surface Film Conditions on Commutation", AIEE Trans., v. 68, pt. 1, p. 106-12, 1949.

40. Moberly, L. E., "Atmospheric Effects on Sliding Contacts", paper presented at Engineering Seminar on Electrical Contacts, Penn. State University, 25-29 June 1956.

41. Elsey, H. M., Moberly, L. E., and Johnson, J. L., "Air Humidity and Brush Contact Drop: The Effect of Water Vapor, Sulfur Dioxide, and Hydrogen Sulfide", AIEE Trans. on Power Apparatus and Systems, no. 15, p. 1383-89, December 1954.

42. Naval Applied Science Laboratory, Project 5332-15, Part 2, Brush Wear in Silicone Vapor Contaminated Atmosphere, by R. J. Katzenstein, p. 4, 7 July 1964.

43. Naval Applied Science Laboratory, Project 9400-7, Mechanism of Siloxone Vapor Induced Excessive Brush Wear in Totally Enclosed DC Motors, by R. J. Katzenstein, p. 9-10, 31 August 1966.

44. Kalb, W. C., "Carbon Brushes for Steel-Mill Equipment", Electrical Engineering, v. 56, p. 1165-68, September 1937.

45. Naval Ship Systems Command,NAVSHIPS 0938-011-4010, Nuclear Powered Submarines Atmospheric Control, December 1967.

46. Naval Ship Systems Command, NAVSHIPS 363-1001, Technical Manual 32.4/10.8 KW DC to 400 Cycle Voltage and Frequency Regulated Motor-Generator Set, Allis-Chalmers, October 1961.

47. Mankonen, H. E., "Constant Force Brush Springs," Electrical Manufacturing, p. 94-97, February, 1956.

48. Shobert, E. I., Carbon Brushes: The Physics and Chemistry of Sliding Contacts, fig. 6:1, Chemical Publishing Company, 1965.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	20
2.	Library, Code 0212 Naval Postgraduate School Monterey, California 93940	2
3.	Naval Ship Systems Command, Code 2052 Navy Department Washington, D. C. 20360	1
4.	Associate Professor Milton L. Wilcox,Code 52Wx Department of Electrical Engineering Naval Postgraduate School Monterey, California 93940	1
5.	LT Philip F. Grasser, USN 501 Ocean Avenue, Apt #18 Monterey, California 93940	1
6.	Mr. Philip Russo Naval Ship Engineering Center, Code 6158E Prince Georges Center Hyattsville, Maryland 20782	1
7.	Mr. George H. Gunnoe Large Motor and Generator Department General Electric Corporation One River Road Schenectady, New York 12305	1
8.	Dr. Erle I. Shobert, II Vice President and Manager of Research Stackpole Carbon Company St. Marys, Pennsylvania 15857	1
9.	Mr. Lawrence E. Moberly Manager, Lubrication and Electrical Contacts Westinghouse Electric Corporation Research and Development Center Churchill Borough Pittsburgh, Pennsylvania 15235	1

DOCUMENT CONTROL DATA - R & D

Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author) Naval Postgraduate School Monterey, California 93940	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3 REPORT TITLE

Effects of Atmospheric Contamination on the Performance of Carbon Brushes on Copper Slip Rings

4 DESCRIPTIVE NOTES (Type of report and, inclusive dates)

Master's Thesis: June 1969

5 AUTHOR(S) (First name, middle initial, last name)

Philip Farr Grasser

6 REPORT DATE October 1969	7a. TOTAL NO. OF PAGES 68	7b. NO. OF REFS 48
8a. CONTRACT OR GRANT NO. b. PROJECT NO c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

10 DISTRIBUTION STATEMENT

Distribution of this document is unlimited.

11 SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Postgraduate School Monterey, California 93940

13 ABSTRACT

The unsatisfactory performance of collector and commutator brushes in motor generators aboard nuclear submarines is introduced with the hypothesis that these difficulties are the result of atmospheric contamination. Following a survey of previously encountered contamination problems the experimental apparatus and procedures used to test this theory are described. Results of operation in eight simulated submarine environments are provided.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Atmospheric Contamination						
Brush Wear						
Collector Performance						
Commutator Performance						